NOT ENOUGH, OR MAYBE TOO MUCH: ASSOCIATIVE DEFICIT VS. HYPER-BINDING MODELS OF AGING IN IMPLICIT LEARNING

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Background. This project investigated the effects of cognitive aging on implicit learning [IL] by testing the competing predictions of two models. One model, the Associative Deficit Hypothesis [ADH], suggests that older adults [OAs] have a specific deficit in their ability to form new relationships in memory, whereas the Hyper-Binding Hypothesis [HBH] suggests that age differences in IL stem from attentional changes in later life.

Aims. We contrasted the predictions of these models by addressing the following aims:

1. Determine whether OAs show more context dependence in IL tasks than younger adults.
2. Determine whether OAs show greater interference from unattended stimuli during IL tasks than younger adults.

Method. We tested context dependence using a novel protocol that manipulated the informativity of objects and their contexts during a word-learning task, and we adapted an established protocol to examine interference from unattended linguistic stimuli.

Results. Neither protocol revealed reliable main effects of age on the learning measure, counter to the predictions of both the ADH and the HBH, although this may be a result of relatively small sample sizes and a wide age range in the older age group. Both experiments provided tentative support of the HBH in their higher-order interactions, but some interactions in the interference protocol contradicted elements of the HBH's predictions. Post-experimental interviews suggested that participants completed the contextual dependence protocol implicitly but may have been explicitly aware of the patterns present in the interference protocol. Future studies

should focus on narrowing the age range of older participants and increasing sample sizes, and in the case of the interference protocol, separating effects of different sources of interference (i.e. interference from attended stimuli versus interference from unattended stimuli.)

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Preface

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1.0 Introduction

According to the US Census Bureau (Ortman, Velkoff, & Hogan, 2014), the number of citizens aged 65 or older is projected to more than double over the next several decades, while the number of citizens over 85 years old is expected to triple. Understanding the typical cognitive aging process is critical to providing appropriate support and care to this growing population. Cognitive aging is complex, affecting multiple skills and resources, and its effects vary across domains and individuals. In some domains, such as processing speed and executive function, older adults tend to perform worse than younger individuals do. In others, such as vocabulary size, older adults show little to no disadvantage compared to younger cohorts. Identifying which aspects of cognition are weakened in aging populations is an important first step in building well-specified models of cognitive aging. Such models might be used to help older adults leverage their strengths and compensate for their weaknesses as they encounter challenges, and they could form a comparative basis for the more precise identification of cognitive impairments in the older population.

One area of contention regarding the aging process is its effect on implicit learning. Implicit learning [IL], or learning without awareness, is a concept developed by Arthur Reber as part of the "cognitive unconscious" which exists separately from conscious cognition and is robust to detrimental influences like disease, injury, and aging (Reber, 1967, 1992). While evidence of the relative age-invariance of implicit cognition compared to explicit cognition does exist (e.g., Aizenstein et al., 2006; Fleischman, Wilson, Gabrieli, Bienias, & Bennett, 2004), Reber himself states that "there are virtually no data that suggest that implicit processes are completely immune to the effects of aging," (Reber, 1992, p. 117). The evidence regarding age effects on IL task performance is extensive and varies based on several task characteristics as explored in a later section. Examining the particular ways in which implicit learning is affected by age could lend further insight into the cognitive aging process as a whole, and the ways for which it can be compensated.

Given the existing base of evidence supporting a relationship between adult age and IL performance, a variety of theories have been proposed regarding the cognitive domains that could be responsible for these age differences. Decreased speed of processing (e.g. Feeney, Howard, & Howard, 2002), attentional deficits (e.g. Nejati, Farshi, Ashayeri, & Aghdasi, 2008a), changes in executive function (e.g. D. V. Howard & Howard, 2001a; Park & Shaw, 1992), a decline in fluid intelligence (e.g. Salthouse, McGuthry, & Hambrick, 1999), and impairments of memory and learning systems have all been suggested as explanations for the decreased IL performance of older adults relative to younger individuals. The experiments described in this document examine models within the memory and learning account of IL age effects, since this cognitive area is the most central to IL as a concept, with the other cognitive areas serving to support the memory and learning processes. These models pertain to a phenomenon within episodic memory known as "associative binding," whereby relationships between elements (whether two objects, an object and its context, specific perceptual features, or other separable entities) are learned. Associative binding [AB] is critical to a wide variety of daily activities such as recalling a person's name upon seeing his or her face or remembering a user name and password for a given website. AB is also arguably the primary goal of IL tasks, which generally require participants to store and retrieve relationships between objects without conscious intervention (see Section II for a more in-depth exploration of this definition.) Thus, the process and products of AB are a natural starting point for explaining age differences in IL, and will be henceforth referred to as the "AB theory" of age effects in IL. AB does not occur in isolation but rather is supported by other cognitive domains, so the accounts involving attention, processing speed, executive function, and fluid intelligence cannot be ignored; the interaction between the AB models and these other accounts is briefly explored in a later section.

The Associative Deficit Hypothesis [ADH] contends that older adults have an association-specific memory deficit that prevents them from learning new relationships, particularly without the use of conscious memory strategies (Naveh-Benjamin, 2000). The hyper-binding hypothesis [HBH] argues instead that older adults instead form too many associations between units of information that are temporally proximal, regardless of cues to the importance of the relationships, creating memory interference that prevents effective retrieval of relationships of interest during learning tasks (Campbell, Hasher, & Thomas, 2010). These two models – one in which older adults store too few associations, and one in which they store too many – interact in different ways with the existing research regarding aging and IL, and are the only two models of AB that have been applied to IL in previous experiments. In determining which of these two models best explains age effects in IL, we may learn how best to support older adults during daily activities that use IL: the HBH might suggest that older adults minimize distractions and work to improve selective attention skills in situations where IL is important, whereas the ADH might suggest that older adults simply compensate for their diminished IL abilities by using external memory aids. Of course, neither model suggests that AB occurs in a vacuum; see Figure 2 for an illustration of how each of these two models fits hierarchically into and interacts with the other cognitive domains listed above.

In this introduction, I will first provide a brief overview of the ADH and HBH. I will then review the existing literature regarding: the nature of IL itself, concerns regarding the interaction of cognitive aging and IL testing, and the various theories of cognitive aging that have been proposed to explain IL age effects. Throughout, I will apply the ADH and HBH to previous empirical evidence and discuss these models' relative strengths and weaknesses in accounting for the observed patterns.

ABBREVIATIONS USED IN THIS DOCUMENT:
IL: IMPLICIT LEARNING, LEARNING WITHOUT AWARENESS
AB: ASSOCIATIVE BINDING, THE LEARNING OF RELATIONSHIPS BETWEEN ELEMENTS
ADH: ASSOCIATIVE DEFICIT HYPOTHESIS, A MODEL OF AB IN WHICH OLDER ADULTS ARE LESS ABLE TO FORM AND STORE ASSOCIATIVE KNOWLEDGE
HBH: HYPER-BINDING HYPOTHESIS, A MODEL OF AB IN WHICH OLDER ADULTS FORM AND STORE TOO MANY ASSOCIATIONS
AGL: ARTIFICIAL GRAMMAR LEARNING, A PARADIGM USED TO TEST IL
SRT: SERIAL RESPONSE TIME, A PARADIGM USED TO TEST IL
ASRT: ALTERNATING SERIAL RESPONSE TIME, A PARADIGM USED TO TEST IL
TLT: TRIPLET LEARNING TASK, A PARADIGM USED TO TEST IL

Figure 1. Abbreviations used in this document

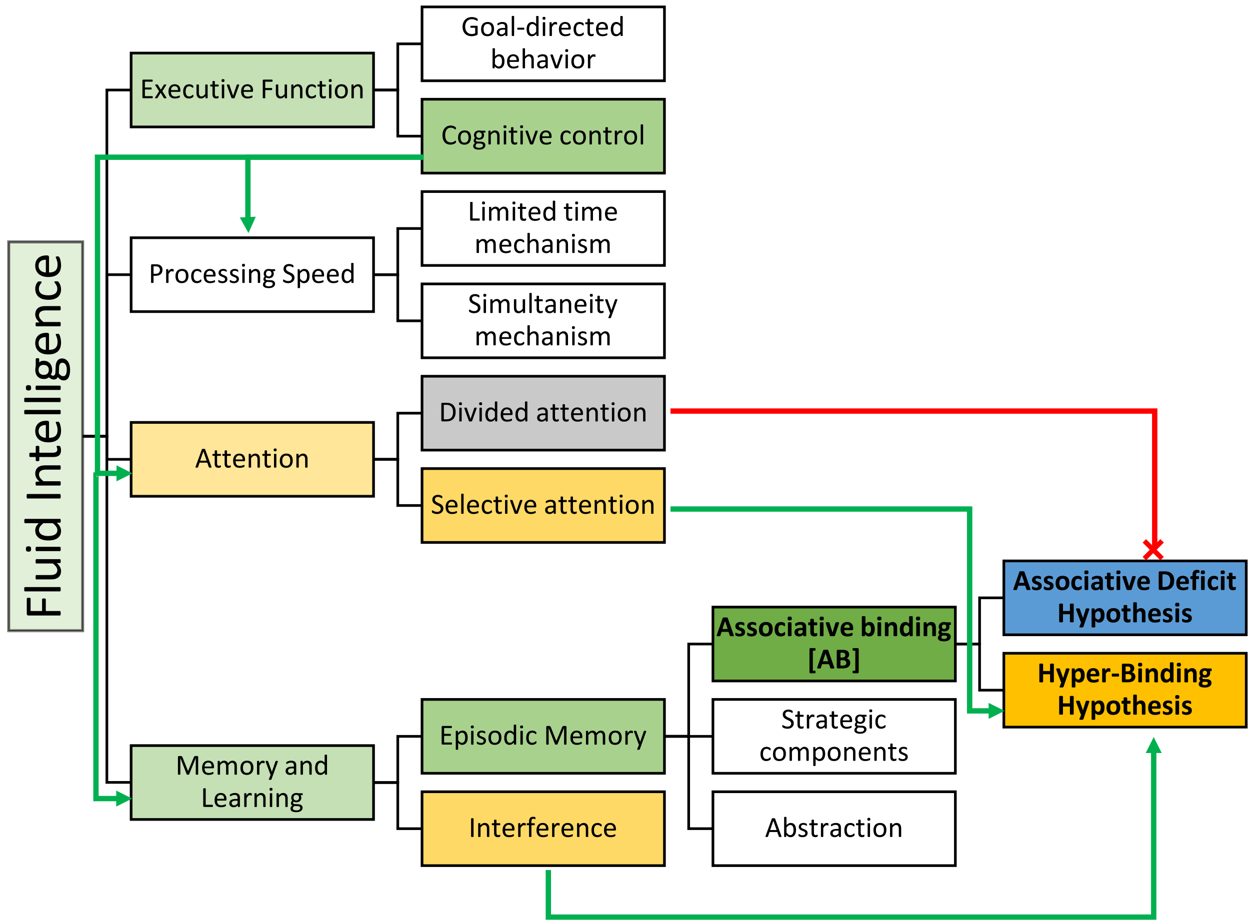

Figure 2: Hierarchy of cognitive domains discussed in this paper. Black lines = direct hierarchical relationships; green arrows = cross-domain influences, red line/X = evidence suggests against cross-domain influence. Items of similar color are related; lighter shades influence darker shades

1.1 **ADH and HBH: A brief overview**

In their most general terms, the ADH and the HBH are competing accounts of the source of older and younger adults' apparent differences in AB. The ADH posits that these differences stem from a reduction in the ability of older adults to form and/or store associative bindings. The HBH argues that this ability is intact, and that differences in associative memory performance are caused by reduced selective attention in older adults, leading these individuals to store irrelevant relationships and experience increased interference during retrieval. In other words, while the ADH predicts that a difference in the process itself leads to fewer stored representations, the HBH suggests that the difference lies in the application of the process leading to excess stored representations.

The Associative Deficit Hypothesis was first articulated by Naveh-Benjamin (2000) based on suggestions by Chalfonte and Johnson (1996) and MacKay and Burke (1990) that older adults experience difficulty "binding information into complex memories." The ADH makes a distinction between memory for individual units of information and memory for relationships between informational units, and argues that the latter is disproportionally affected by aging. The theory does not differentiate types of relationships (e.g. object-object associations versus object-context associations). The foundational tasks for testing the ADH have been paired-associate learning tasks, where participants studied index cards with pairs of items on them and later completed recognition tests of the items and the item pairs. These recognition tasks required participants to identify the items or item pairs they had encountered during the study phase within a field that also contained novel items or recombined pairs. The interaction between age and test is the critical effect: older adults should do worse on the pair tests than on the item tests, regardless of the item type or the nature of the relationship being tested.

The experimental evidence for the ADH will be examined in detail in a later section, but some key points of the hypothesis and its application to IL arise from empirical findings and thus will be briefly outlined here. First, patterns in the foundational Naveh-Benjamin (2000) study suggest that age-related differences in incidental learning of word pairs (a case of IL) are smaller than the age-related differences seen for intentional learning. In other words, the direction of conscious effort toward learning associations does not improve associative learning in older adults as much as it does in younger adults (see Figure 3), suggesting that the age-related associative deficit applies both to explicit and implicit learning conditions. Later findings (Naveh-Benjamin, Brav, & Levy, 2007) suggested that this age gap in explicit learning could be ameliorated by prompting older adults to use an associative strategy, suggesting that a lack of spontaneous strategy use (e.g., elaboration) in older adults may contribute to age-related AB differences, but consciously cueing strategy use is inherently not possible during IL.

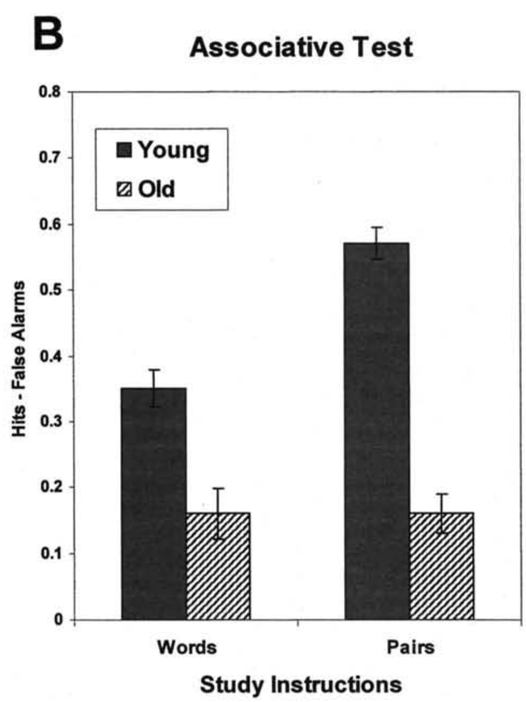

Figure 3: Response patterns in initial study supporting the ADH. Proportion of hits minus proportion of false alarms in the associative recognition test for younger and older participants in different study instruction conditions: Words = incidental, Pairs = intentional learning of the associations (Naveh-Benjamin, 2000, p. 1175)

The authors propose "schematic support, in which incoming information can be supported by existing connections between the components in memory," (Naveh-Benjamin et al., 2007, p. 207) as an alternative manipulation to ameliorate age-related differences in associative learning. The idea of "schematic support" was tested by replicating the paired-associates task comparing memory for pairs of related words to pairs of unrelated words (Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). Younger adults' relative performance on the item and item-pair tests was unaffected by the relatedness of the word pairs. Older adults performed worse on the pair test than on the item test when the pairs were unrelated, but performed equivalently on the two tests when the pairs were related. Finally, in the same study, the authors investigated one type of attentional resource reduction by dividing a group of younger adults' attention using a secondary task. These younger adults performed worse overall, but did not perform disproportionately worse on the item-pair test compared to the item test, nor did the relatedness of the word pairs disproportionally affect their item-pair performance (see Figure 4.) The authors suggest that this result contradicts arguments that older adults' poorer performance on associative tasks could be caused by attentional issues. Because the dual-task manipulation tests divided attention, however, this manipulation does not test the potential mechanism underlying the hyper-binding hypothesis: reduced selective attention.

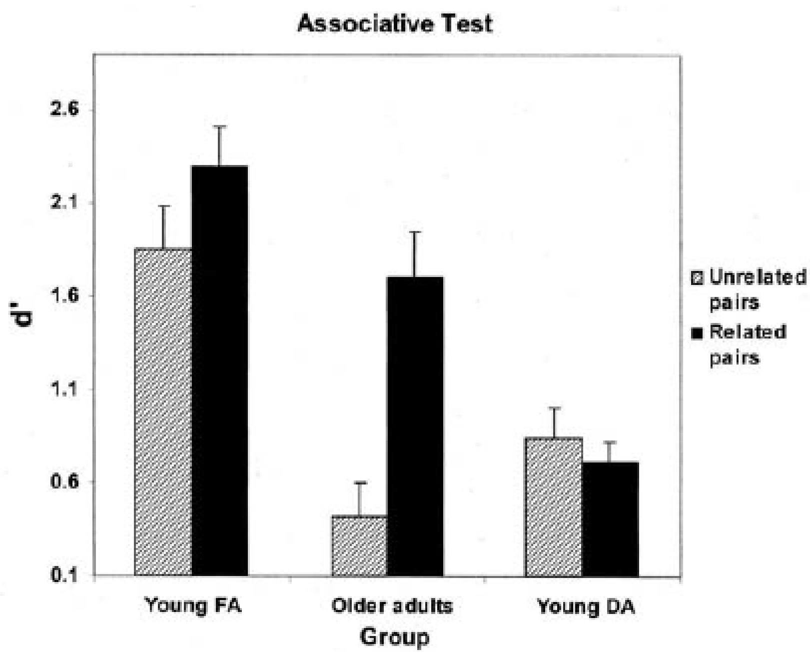

Figure 4: d' discrimination measure in the associative-recognition test across relatedness conditions. Young FA = young full attention, Young DA = young divided attention. (Naveh-Benjamin et al., 2003, p. 832)

In opposition to the ADH, the hyper-binding hypothesis argues that older adults make excessive associations. This hypothesis was first proposed by Campbell, Hasher, and Thomas (2010). It stems from observations of reduced inhibitory control in older individuals (e.g. L Hasher, Zacks, & May, 1999), leading to a wider "bandwidth of attention" (Campbell, Hasher, & Thomas, 2010, p. 399) for older adults than for younger adults. These observations are coupled with findings of older adults' tendency to show outsized effects of distraction during experimental tasks (e.g. Lustig, Hasher, & Tonev, 2006) and to encode nonrelevant, distracting information (e.g. Kim, Hasher, & Zacks, 2007). Given this constellation of findings, the authors hypothesize that "age differences in associative memory may be caused… by interference from excessive binding," (Campbell, Hasher, & Thomas, 2010, p. 404). Therefore, the HBH proposes that older adults' reduced selective attention, not the divided attention examined by Naveh-Benjamin et al. (2003), may be at the root of age-related associative learning differences.

Again, the evidence supporting the HBH will be thoroughly examined in a later section, but the few existing studies provide important points for consideration while exploring general trends in IL and aging which are outlined here. Campbell and colleagues generally tested the HBH by exposing participants to simultaneous streams of information, usually during an n-back task, and instructing the participants to attend to only one of the streams. This is again an IL task, since the target to be learned (the sequence of non-response items in both the attended and unattended streams during the n-back task) was not the focus of the task, making it unlikely that participants would attempt to learn the sequence through conscious effort. They followed this period of exposure with tasks that tested the participants' memory for the attended and the unattended information. In the original 2010 study, the concurrent streams were a set of pictures on which the n-back task was performed, and a set of words presented above the pictures that participants were instructed to ignore. A subset of the pictures had individually-assigned words with which they were always shown. Following the n-back task, participants completed a paired associates task like those Naveh-Benjamin and colleagues used, where they learned picture-word pairs that were either intact from the n-back task, recombined pairs from the n-back task, or totally novel word-picture pairs. Younger adults performed similarly on this learning task regardless of pair type, whereas older adults showed a memory advantage for intact pairs relative to novel pairs, and a disadvantage for recombined pairs relative to novel pairs. In a follow-up study (Campbell et al. 2012), participants performed an n-back task on one set of pictures while ignoring a set of differently-colored pictures that were interleaved between presentations of the target pictures. Each set consisted of triplets of pictures which always appeared in order. During the testing phase, participants performed a speeded-detection task where they were instructed to identify a specific picture from either the target or nontarget set when several of the triplets were presented in sequence. Older adults showed learning effects from both the target and nontarget picture sets on this task, whereas younger adults showed only effects from the target set.

These studies demonstrate that when informational units, whether like (picture-picture) or different (picture-word) are presented in close temporal proximity, older adults are likely to store associations between them regardless of instruction to ignore the information, whereas younger adults will not store these associations if they are told not to. The findings directly contradict those supporting the ADH, which appear to indicate a reduction in retained associations in older adults. Supporters of the HBH argue that memory interference causes older adults' apparent lack of stored associations: a larger amount of stored associations could increase interference during memory tasks, causing the disadvantage for older adults observed in the ADH literature. Given these empirical bases for the two opposing hypotheses, a few questions are important to keep in mind while evaluation of the existing IL and aging literature using an associative binding framework: First, is it possible that spontaneous conscious strategy use in younger but not older adults could account for any observed age differences, as demonstrated in Naveh-Benjamin (2000) and Naveh-Benjamin et al. (2007)? This possibility may be controlled either via design of the training task or via post-hoc evaluation of participants' conscious awareness of the task, but without this information the possible discrepancy in strategy usage remains a concern. Second: in cases where age differences are not observed, could the stimulus items have a pre-existing relationship to facilitate associative binding in older adults, as described by Naveh-Benjamin (2003)? Third, in cases of IL age effects, are there distractor stimuli presented in close temporal proximity to the target stimuli, which might lead to extraneous associations being built in a hyper-binding model (e.g. Campbell et al., 2010)? Finally, do experiments with more distractors or distractors that are more similar to the target stimuli result in larger age differences in IL, indicating a memory interference effect? Each of these issues were either controlled for or directly manipulated in the studies described in this document.

1.2 **Implicit Learning**

The definition of "implicit learning" is not widely agreed upon, but without a well-specified definition it is difficult to identify the scope and relevance of a given IL phenomenon, or to choose tasks that are best suited to testing IL. While most researchers agree that hypothesis-driven, intentional learning resulting in consciously-accessible products should be considered "explicit," (Reber, 1992) the characterization of implicit learning is less consistent. The challenge of defining IL arises from several sources, and has been written about at length (e.g., Cleeremans, 2005; Frensch, 1998). In this section, I explore both the concept of "implicitness" and the ways in which that concept has been applied to models of learning and its products. Doing so will provide a foundation for evaluating IL tasks in general and the theories that pertain to them, as well as a starting point for understanding the AB models in specific.

1.2.1 **Challenges in Defining "Implicitness"**

Of the challenges involved in defining IL, perhaps the most difficult is deciding what it means for knowledge or processes to be "implicit" and, conversely, the meaning of being "conscious" of something. Frensch (1998) argues that researchers tend to use "conscious" and/or "explicit" to refer either to awareness or to intentionality in the implicit learning research. Of course, the words "aware" and "intentional" also lack appropriately specified definitions but some distinction between these two concepts is usually made, and so these different meanings must either be incorporated or excluded from a theoretically satisfying definition of implicit learning. Reber also focuses on both awareness and intention in his discussion of consciousness, describing conscious learning as "reflective, overt, and declarative," (Reber, 1992, p. 113), and asserts that this type of cognition is relatively late-emerging in both evolutionary and developmental terms. Shanks and St John (1994) focus on awareness in their discussion of consciousness, and examine the difficulties involved in examining awareness empirically. They argue that testing at the time of learning changes the nature of the learning itself, making it more likely to become explicit. However, testing afterward for conscious awareness creates the possibility for conscious awareness to be generated through the individual's own self-examination of their responses, or for conscious awareness during the task to have been forgotten.

Cheesman and Merikle (1984) also focus exclusively on the examination of awareness in their exploration of the meaning of consciousness. Based on empirical data, these authors argue that there exists a difference between "subjective" awareness, when an individual endorses that they have experienced a stimulus in an open-ended context, and "objective" awareness, when an individual can respond appropriately to a forced-choice recognition of the stimulus. This distinction is an interesting one, in that it offers a potential middle-ground between strong claims of implicit cognition, that it is fully distinct from explicit cognition (Lewicki, Hill, & Czyzewska, 1992; Reber, 1992), and strong claims against implicit cognition, that it is largely unproven when appropriate methods are used to test for explicit awareness (Shanks & John, 1994). In this compromise, "implicit" could refer to that knowledge which is above an individual's objective threshold but below his or her subjective threshold; he or she "knows" but does not "experience knowing." Unfortunately, this middle ground is largely unexplored by authors interested in implicit learning.

Reingold and Merikle (1988), on the other hand, avoid the issues of "awareness" and "intentionality" altogether. They distinguish implicit from explicit knowledge based on measurement sensitivity. In this model, some knowledge is most sensitively detected through direct testing – a task in which the individual's target response is the measure of interest. For example, if an experimenter wishes to measure directly whether or not participants perceive the written word in a Stroop-like stimulus, the experimenter could instruct the participants to read the word aloud or to identify the word in a forced-choice task. Conversely, other information is most sensitively detected through indirect testing – a task in which the individual's target response is not the measure of interest. If the goal were to measure word perception in a Stroop-like stimulus indirectly, the experimenter could instruct the participants to name the color in which the word is written, and compare the participants' accuracy or response times on trials where the word and color are congruent to those where they are incongruent. This type of analysis acknowledges that the concepts of consciousness and unconsciousness may not be mutually exclusive, and that knowledge and abilities may fall on a continuum between the two; as pointed out by Rieckmann and Bäckman, "the influence of explicit processes upon IL has been widely debated [...] and [implicit learning] and [explicit learning] tasks are probably never fully dissociable," (2009, p. 491). Jimenez, Mendez, and Cleeremans (1996) applied this principle to a traditional implicit learning task involving serial response time (SRT, see the following section for a discussion) to a training sequence, which is considered an indirect measure of sequence knowledge: the participant identifies the location of a stimulus, but his or her knowledge of the sequence affects how quickly that identification can be made. This indirect measure was contrasted with a direct measure of sequence knowledge, wherein participants indicated where they expected the next stimulus to appear. While a small amount of sequence knowledge was detected by the direct measure, a much larger effect size was detected by the indirect measure. So, while both direct and indirect measures detected learning in the task, the indirect measure appears to have been more sensitive – a suggestion that the resultant knowledge falls closer to "implicit" than to "explicit" on the spectrum.

In general, these explorations of "implicitness" fall into two categories: those that focus on the learner's internal cognitive state (i.e. Shanks & St John, and Cheesman & Merikle,) and those that focus on the learner's external learning behaviors (i.e. Reingold & Merikle, and Jimenez, Mendez, & Cleeremans.) Many researchers focus on the first, internal definition of "implicitness" when writing about their studies, but the vast majority of IL tasks use indirect measurements to operationalize IL success, so it seems that the field as a whole accepts elements of both definitions in the collective understanding of IL.

In terms of the AB models in question, only the ADH deals directly with ideas of "implicitness." As described in the previous section, Naveh-Benjamin and colleagues have consistently found that intentional learning task conditions exacerbate age differences in performance (e.g. Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2007). They explain this phenomenon by suggesting that older adults' underlying associative difficulties prevent them from benefitting from intentional learning techniques in the same way younger adults can. Given that learning success in these studies was operationalized using a direct measure (accuracy,) they appear to have evaluated both implicit and explicit learning conditions (defined subjectively, c.f. Shanks & St John) using a measure most sensitive to explicit learning (defined behaviorally, c.f. Reingold & Merikle,) making these patterns difficult to interpret cleanly. Ideally, as in the experiments described in Chapters 3 and 4, studies regarding AB in relation to IL should use both direct and indirect measures of learning to avoid such confounds.

1.2.2 **Challenges in Defining "Learning"**

In addition to distinguishing the "explicit" from the "implicit," an acceptable definition of implicit learning must distinguish this concept from other aspects of what Reber refers to as "cognitive unconscious," (Reber, 1992). The distinction between "implicit memory" and "implicit learning" is difficult to define, as the two concepts share many similarities (Buchner & Wippich, 1998; Seger, 1994). They are, however, generally considered to differ in some respects: tests of implicit memory are designed to examine exposure to single stimuli and the retrieval of those stimuli at a later time, while implicit learning examines the acquisition and use of the relationships between multiple stimuli (Rieckmann & Bäckman, 2009; Seger, 1994); in other words, only tasks that require AB are universally recognized as IL tasks. For this reason, linguistic priming studies are typically considered to examine only implicit memory and not implicit learning, and will not be included in this review.

Similarly, some researchers refer to skill learning – such as rotor pursuit and mirror tracing – as "implicit," because they result in non-declarative memory products and can be dissociated from traditional explicit learning. These tasks, however, usually involve knowledge of the target outcome of the skill and some level of hypothesis-driven behavior is usually undertaken to get there, injecting elements of explicit learning behavior into these tasks (Rieckmann & Bäckman, 2009). Therefore, this type of skill acquisition is also excluded from most definitions of implicit learning. Additionally, some studies of implicit processing have examined responses to stimuli presented below the conscious threshold, referred to as "subliminal learning." These effects are incredibly limited compared to other implicit learning tasks, and so most researchers exclude subliminal learning from their definitions on the basis of this empirical divide (Frensch, 1998). So, we have a clear idea of the boundaries separating IL from other concepts in implicit cognition: it is not memory without associative elements, it is not skill learning, and it is not subliminal learning.

These types of exclusionary definitions are ultimately unsatisfying, as they leave the theoretical underpinnings of implicit learning largely unspecified. In an attempt to find commonalities among definitions of IL that could provide a more inclusionary definition, Frensch (1998) acknowledges three phases in any learning process: perception of the stimulus, acquisition of the target information, and retrieval of that knowledge. According to Frensch, most definitions of implicit learning require that the first phase is not implicit, because implicit perception would classify the learning experience as subliminal rather than implicit. The second stage is the most widely agreed-upon by implicit learning researchers; the acquisition of the knowledge should be implicit in IL, if it is to be distinguished from other types of learning. No such consensus exists for the third stage – some researchers consider knowledge to have been implicitly learned even if it is accessed consciously, whereas others reject the idea that consciously accessible information could possibly have implicit origins. This three-stage model provides a starting point for an inclusionary definition of IL: the implicit acquisition of the target information, presumably by either definition of "implicitness" as discussed in the previous section, is necessary (and, to many researchers, sufficient) for a given learning experience to be considered IL.

The ADH suggests that older adults' reduced IL performance arises from reduced capacity to execute the second, "acquisition" stage of learning. By contrast, the HBH suggests that differences during the "acquisition" stage (namely, reduced selective attention leading to the over-acquisition of relationships) lead to further difficulties during the "retrieval" stage (namely, excess interference.) In other words, the HBH argues that older adults perform differently across stages of the learning experience, whereas the ADH argues that their performance differences are localized to a single stage of the process.

In summary, while currently researchers can generally agree upon what implicit learning is *not* – it is not intentional or hypothesis-driven, it is not skill learning or implicit memory, and it is not an acquisition of consciously accessible abstract rules – there is also a growing consensus on what implicit learning *is*. In Frensch's discussion of a three-phase model of learning (Frensch, 1998), he argues that most definitions of implicit learning require both: (a) *conscious processing of the stimuli* and (b) *unconscious acquisition of the relevant information*, despite disagreement on whether or not that information must be inaccessible to conscious retrieval. This commonality provides a starting point for qualifying tasks as IL-based or not, and for continuing to build and test theories of IL.

1.3 **Implicit Learning and Aging: Issues of Measurement**

As with most cognitive behaviors, implicit learning can be measured in many ways. The characteristics of the different measures may provide specific benefits, challenges, and limitations when implemented with older participants, especially given the task-dependence of implicit learning in general (Cleeremans, 2005). In this section, I provide necessary context for the tasks implemented in the current experiments by exploring considerations relevant to testing implicit learning in general, and to testing the aging population in particular, and summarizing the existing evidence regarding these concerns. Throughout, I will apply the ADH and HBH to each concern and generate relevant predictions, then discuss the relevant empirical evidence and compare it to those predictions. These comparisons are critical for understanding which testing methods are most appropriate for contrasting the two competing models, and for constructing interpretations of the evidence for and against each model. Ultimately, understanding the way that the varying IL tasks interact with each of the models should enable the current studies' conclusions to be most appropriately applied to the provision of environmental support and/or compensatory strategies to older individuals struggling with IL in daily activities.

1.3.1 **Levels of Complexity: Structure of the AB relationships to be learned**

When researchers measure implicit learning, the nature of the regularity to be learned, as well as its structure and complexity, must be identified. Most implicit learning tasks investigate the acquisition of a regularity within a set of symbols or events (hereafter referred to as "elements.") The most basic ways a researcher can manipulate the complexity of a regularity are by changing the number of possible elements (for example, a grammar made of eight letters has eight possible elements), or by changing the number of elements in the sequence (for example, a repeating sequence in a 36-trial serial response task [SRT, see section on Task Characteristics for a description] might be twelve elements long and repeated three times, or it might be four elements long and repeated nine times.) According to the ADH, older adults have relatively intact memory for items, so increasing the number of possible elements should not have an outsized effect on aged learners. Conversely, increasing the number of elements in the sequence increases the number of associations that must be stored, which should lead to a larger disadvantage for older adults than younger participants due to their reduced associative binding resources. The HBH, which is based on reduced inhibitory control in older adults, does not predict a selective effect of sequence length on older adults; rather, since reduced inhibitory control likely leads to larger interference effects in older adults (e.g. Shimamura & Jurica, 1994), increasing either the number of elements or the length of the sequence should disadvantage older adults by increasing the opportunity for elements in the sequence to interfere with one another. In other words, the HBH predicts an aging effect of both the number of elements and the sequence length, whereas the ADH predicts that only sequence length should show an aging effect. Of course, comparing sequences of different lengths raises concerns of separating the effects of sequence length from the effects of either the number of exposures to each stimulus (if the total number of trials is held constant) or the number of trials (if the number of exposures to each stimulus is held constant). For this reason, the current studies do not test these predictions, but they are important to keep in mind while reading and evaluating previous evidence regarding IL.

Implicit learning research in aging tends to focus on sequential regularities, using the SRT, alternating SRT, or Triplet Learning Task [ASRT and TLT, see section on Task Characteristics for descriptions] paradigms. These tasks all use patterns of elements, presented in series. Although the temporal characteristics of these series may vary – elements in the sequence may be presented individually or in groups – the order in which the elements are encountered by the learner is important to these regularities.

Sequential regularities may have dependencies or probabilities that occur at different "levels." At the lowest level, some individual elements may be more common than others, providing what is called a zero-order structure. If some pairs of elements occur more often than other pairs, the regularity is considered a first-order structure; if some triplets occur more frequently than others, a second-order structure is present; and so on (J. H. Howard & Howard, 1997). In general, research has found that higher-order structures are more difficult for participants to learn than lower-order structures (D. V. Howard et al., 2004; J. H. Howard Jr., Howard, Dennis, & Kelly, 2008). This statement is complicated by the fact that in any given sequence, several order structures may be present: the sequence 12341234 has no zero-order structure, as all elements are present at the same frequency, but has first-order structure since the pairing 12 is more common than the (absent) pairing 13. The pattern also has second-order structure, since the triplet 123 is more common than the (absent) triplet 134 is, and third order structure since the quadruplet 1234 is more common than the (absent) quadruplet 1342. This means that performance on two tasks with similar minimal structures may be affected by differing higher-order structures.

Since the ADH argues that older adults have intact memory for items but impaired memory for associations, it predicts that zero-order structures should not show an aging effect, but higher-order structures should. The HBH does not predict such a selective effect; so long as other factors (such as number of elements and sequence length) are equal, the HBH predicts that older adults should be as good as or better than younger individuals at remembering the individual relationships that make up a sequence, so a difference in age effects between zero- and first-order structures should not be observed. That being said, the HBH relies on temporal proximity as the primary impetus for older adults to construct associative bindings (Campbell, Trelle, & Hasher, 2014), so higher-order structures that require participants to remember relationships across multiple trials (e.g. sequences in which 1XX4 is more common than 1XX3, where X represents any of the possible elements) might be disadvantaged for older adults. Alternately, since the HBH predicts that older individuals store and retrieve more relationships than younger adults, it is possible that higher-order structures that are unintentionally included in a sequence might be retained by older but not younger adults, and thus might disproportionately interfere with older adults' performance. In sum, the ADH predicts an age effect on any structure above zero-order, while the HBH predicts equivalence between zero- and first-order structures at minimum, but could account for age differences in higher-order structures. Of the four current experiments, the first set of two uses only a second-order structure, but the second set contains both first- and second-order regularities. If age differences are smaller in the second set than they are in the first set, this could be construed as evidence for the HBH, although it would be relatively weak evidence compared to the main comparisons of interest within each set.

1.3.1.1 **Empirical findings.** Several research studies have examined how sequence complexity interacts with aging in implicit learning. Howard et al. (2004) compared second- and third-order structure learning in younger and older adults, using a standard four-element, second-order structured ASRT in comparison with a modified, third-order structured ASRT containing two random trials between each sequence trial (represented symbolically: 1rr2rr3rr.) It should be noted that this manipulation of sequence structure also changes the amount of random noise within the sequence. In this study, younger participants showed larger learning effects on both RT and accuracy than older participants did, and only younger participants showed learning effects in the third-order structure task. These results were further explored in a subsequent study (Bennett, Howard, & Howard, 2007), which reduced the number of possible elements in the sequence from four to three. With this modification, younger and older participants showed similar ultimate learning effects on RT, although younger participants showed a significant effect of learning earlier in training. Younger adults also showed larger learning effects on accuracy than older adults did, but older adults did show a learning effect, in contrast to the absence of an effect in the previous four-element study. These results illustrate the multifaceted nature of task complexity in

IL tasks: both the number of elements in a sequence and the structure of the sequence itself appear to have differential effects on aged versus younger adults, and some measures (i.e., RT) appear to be less sensitive to these effects than others (i.e., accuracy).

A similar comparison of second- and first-order structures was conducted using a modified 4-element SRT task (Curran, 1997). Each sequence was twelve elements long. The first-order sequence contained some frequent pairs (e.g. AB) and some infrequent pairs (e.g. AD) while excluding some other pairs (e.g. AC), and these pairs were combined in such a way that some triplets (e.g. ADB) occurred more than once. In the second-order sequence, all pairs occurred equally often, but each triplet (e.g. ABA) occurred only once. Participants responded to twelve-trial runs of the entire sequence alternated with twelve-trial runs of randomly generated elements. This modification allowed for within-block comparison of patterned and random trials without eliminating the possibility of first-order structure in the target sequence. Examination of the accuracy data revealed that the older subjects were more accurate than younger participants were, suggesting a different speed-accuracy trade-off approach than the younger adults. Both older and younger participants showed learning effects on response accuracy, though these effects were larger for younger participants. No reliable effects of sequence type on accuracy were found. Given large differences in RT, direct comparisons across age group were not made on this measure. In each group, younger participants showed similar RT-based learning effects across the two types of sequences, while older participants showed larger learning effects for the second-order sequence than the first-order sequence. It may be that this counterintuitive pattern was caused by more complex higher-order characteristics of the first-order sequence. Simply put, while the second-order sequence could be learned by memorizing the triplets from which it was constructed, the first-order sequence required participants to remember longer “chunks” in order to reproduce it accurately. This interpretation is supported by a later investigation (J. H. Howard Jr. et al., 2008), which used a TLT approach and found that again, younger participants showed equivalent performance on first- and second-order structures, but revealed that older participants showed larger learning effects for first-order sequences than second-order structures in an environment where higher-order structures were removed. This pattern of results emphasizes that researchers cannot focus exclusively on the lowest-order structural characteristics of a target sequence, as concurrent higher-order characteristics can influence results.

The fact that *both* the number of elements (Bennett et al., 2007) and the amount of noise present in the sequence (D. V. Howard et al., 2004) negatively affected older adults' performance is more consistent with the predictions of the HBH than the ADH, since the ADH does not predict an effect of the number of elements. Older adults' better performance in situations where they needed to remember shorter "chunks" in order to produce the entire sequence accurately is consistent with the HBH's prediction that longer sequences are vulnerable to interference effects, but also with the ADH's assertion that older adults simply remember fewer relationships overall.

It is clear that sequence length and complexity are significant influences on task performance, and that the ADH and HBH interact with them differently, but specific effects are still largely unknown. The current studies address two different types of relationships: one involving first-order associations (pairs of objects and contexts, in which some pairings are more frequent than others) and one involving both first- and second-order associations (invariant triplets of words or nonwords.) While the studies do not directly test the effects of complexity on performance, testing across sequence complexities allows confidence that any observed behaviors are not simply the result of a particular complexity level.

1.3.2 **Task Characteristics**

1.3.2.1 **Sequence-learning tasks.**

Artificial grammar learning. Research on sequential regularities tends to be conducted using either an artificial grammar learning (AGL) task or a serial response time (SRT) task. Stimuli for traditional AGL tasks, which were first introduced by Miller (1958), consisted of letter strings which were generated using a set of rules (see Figure 5). As first implemented in implicit learning research by Reber (1967), participants were instructed to memorize these letter strings in successive, small sets without being informed of the existence of the generative rules. A reduction in errors in later sets, when compared to the performance of individuals memorizing randomly generated letter strings, indicated that implicit learning of the underlying regularity facilitated memorization of the strings. Later experiments gathered more traditional measures of implicit knowledge by implementing a test phase after the memorization task, where participants were informed that the strings they had memorized followed a set of rules and instructed to categorize each of a set of novel strings as either grammatical or not (Reber, 1967). This testing phase allowed collection of reaction time data as well as accuracy (Midford & Kirsner, 2005). Thus, several possible indications of sequence learning are available: increased accuracy in memorization of patterned series compared to nonpatterned series, accuracy in the categorization of novel strings, and decreased RT when categorizing patterned strings when compared to nonpatterned strings.

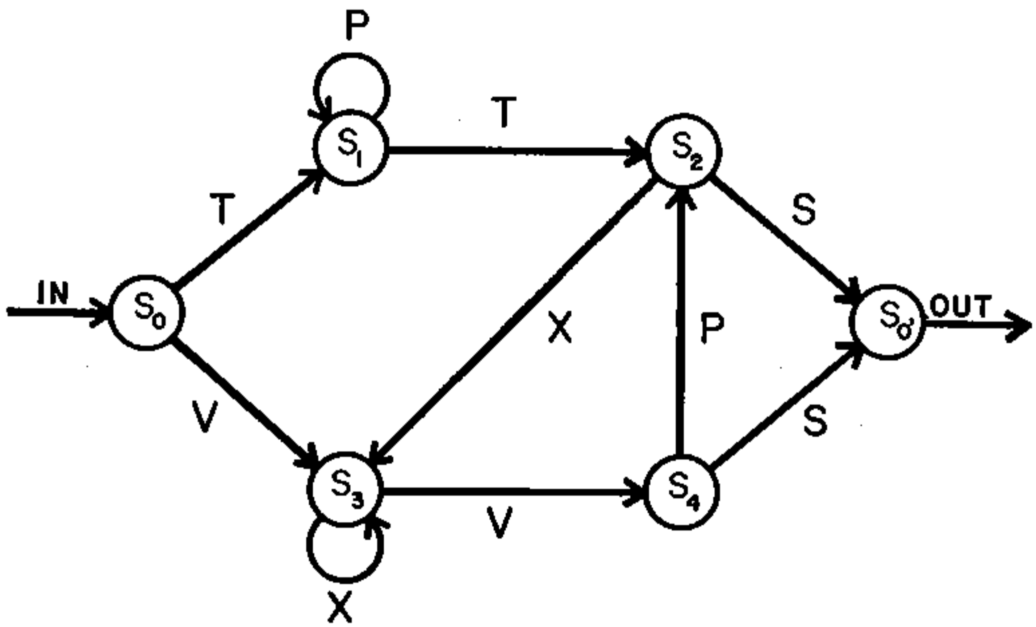

Figure 5: Schematic state diagram of Reber's (1967) artificial grammar

Since neither set of the current studies use the AGL paradigm, application of the ADH and HBH predictions regarding this paradigm must be limited to the existing evidence. Assuming that participants direct conscious effort toward learning the letter strings (albeit not toward learning the underlying structures), the ADH predicts that this task should amplify existing age effects: as discussed above, conscious effort facilitates associative learning in younger adults but the selective associative impairment in older adults prevents them from experiencing this "boost." Logically, this means that the ADH predicts a large increase in performance from the randomly-generated strings to the grammatical strings for younger adults, and a smaller increase for older adults. If the agrammatic control strings are presented separately from the grammatically-structured strings, the HBH does not predict a strong age-related task effect for this paradigm; if, however, the control strings are presented alongside the grammatical strings, the HBH predicts a larger disadvantage for older individuals as they would experience outsized interference effects from these strings. The high probability that participants might direct conscious effort toward discerning the underlying structure of the letter strings significantly complicates these predictions, however, and is in large part why the current studies below avoid this paradigm entirely.

Serial response time. While the use of the AGL task has a long-standing history, it has become unpopular in the study of implicit learning as serial response time (SRT) tasks have been adopted. In the traditional SRT task, as introduced by Nissen and Bullemer (1987), a target marker appears in one of four positions on a computer screen, and the participant must press a key or button that corresponds to the target's position. Participants complete many of these trials, divided into experimental blocks. In sequence-learning blocks, the target's position is determined by the regularity to be learned (each position makes up one element in the sequence,) while in control blocks the target's position is randomly generated. Participants are not informed of the existence of an underlying sequence, and are only told that the task is a test of reaction time and accuracy. Sequence-specific learning can be distinguished from general skill learning by comparing the accuracy and/or speed of participants' responses in a patterned block to their responses in a control block. If participants have learned the sequence, they can use it to predict upcoming patterned stimuli, allowing them to respond more quickly and accurately, but they cannot predict trials that do not follow the learned sequence.

The SRT task has some advantages over the traditional AGL task. First, the participant responds to each element in the sequence individually, yielding a much higher-resolution dataset than the single response to a string of multiple elements in the AGL task. Additionally, the SRT task encourages engagement with each element in the sequence without encouraging participants to focus on explicit memorization. The SRT design has also been found to elicit reliable results at an individual-differences level (Salthouse et al., 1999).

Some differences may make this task undesirable, however: the one-to-one mapping of sequence element to response button means that task performance relies on motor sequencing ability, so it may not be appropriate for populations with known motoric deficits. Additionally, this traditional version of the task uses visual-spatial stimuli, a modality that may not be desirable for all populations (see section on Spatial Ability for further discussion). Finally, the blocked design of the traditional SRT task may lead to difficulties in interpretation of results because RT and accuracy tend to improve throughout the task (due to general adaptation to the task,) so comparison of consecutive patterned and random blocks may suggest artificially large or small effects of sequence-specific learning. The blocked design may also encourage some explicit processing of the sequence, due to the uninterrupted presentation of the sequence without noise.

Assuming that explicit processing of the sequence does not occur, the ADH should predict smaller age effects for this task than for the AGL task, since the younger adults' associative learning is no longer facilitated by conscious effort. If, however, explicit processing does take place, the ADH should not anticipate further task-related age differences between the AGL and SRT tasks. The HBH, on the other hand, should predict that interspersing the sequenced blocks with the random blocks will increase prospective interference for older adults as compared to younger adults as the experiment progresses, leading to a diverging performance pattern between younger and older adults as a function of time, although the temporal separation between the random and sequenced trials may ameliorate this effect somewhat. Since the current experiments do not use a blocked design, these predictions must again be evaluated only on the basis of previous studies.

Adaptations of the serial response time task. Given the previously-explored disadvantages to the SRT, two popular adaptations of the task have been developed by Howard, Howard, and colleagues. The first, an alternating SRT (ASRT) task (J. H. Howard & Howard, 1997), intersperses patterned trials with random trials instead of grouping patterned and random trials into separate blocks. This means trials are presented in the order 1r2r3r4r, where the numerals represent elements of the target sequence and the letter 'r' represents randomly generated elements. This adaptation eliminates the blocking-related problems of pattern-to-control comparison: since both trial types are presented throughout the experiment, artificially decreased or increased sequence-specific learning effects due to general skill learning is not possible. Additionally, the alternating nature of the task introduces noise to the sequence presentation, which may decrease participants' explicit recognition of the target regularity (J. H. Howard & Howard, 1997). The alternating nature of the task, however, also means that first-order structures (that is, more frequent pairings of some elements than of others) are not possible. A target sequence with first-order structure is by nature transformed into a second-order structure with the interspersion of the random trials, which makes any given pairing of elements as likely as any other.

The ADH should not predict age-related task effects of the ASRT as compared to the SRT task beyond those created by the reduced probability of explicit processing. The HBH, however, should entail that the additional noise will lead to increased interference effects in older adults as compared to younger adults. This, combined with the necessarily higher order of the target sequence and the increased temporal distance between target sequence elements, should lead to larger age-related task effects for the ASRT as compared to the SRT task.

The second adaptation of the SRT is the Triplet Learning Task (TLT; J. H. Howard Jr. et al., 2008). In this task, elements are presented in groups of three: two cue events, and a target event. Participants view the two cues and then respond to the target. Researchers can manipulate the frequency of the entire triplet, or the frequency of the co-occurrence of one of the cues and the target. Participants' accuracy and speed of response to these higher-frequency targets can be compared to randomly generated or otherwise low-frequency targets, in order to determine whether participants have learned the underlying statistical regularity. By only requiring a response to every third element, the TLT significantly reduces the motor sequencing demands presented by the SRT. Similar to the ASRT patterned and random trials of the TLT can be interspersed, reducing the likelihood of explicit sequence recognition and allowing more direct comparison of trial types. Additionally, the TLT is not limited to second-order structures like the ASRT: the experimenter can choose to manipulate the co-occurrence of the second cue and the target, a consecutive pair, in addition to the entire triplet or the first cue and target (both of which would be examples of second-order structures).

Because the TLT is so flexible, the predictions of the HBH and ADH depend on the groupings and sequence types chosen by the experimenters. If random and sequential trials are blocked, predictions will resemble the SRT task more closely, whereas if they are interspersed, they will resemble the ASRT.

Empirical findings. While the particular results of age comparison on each of the previously discussed tasks vary from study to study, some prototypical patterns emerge. For example, several studies on aging effects in the basic SRT task (Frensch & Miner, 1994; D. V. Howard & Howard, 1989, 1992) found that older adults tended to respond more slowly overall than younger adults to stimuli, but that the learning effect on RT observed by comparing patterned to non-patterned blocks did not significantly differ between age groups. It appears that these longer RTs reflect a differing speed-accuracy trade-off strategy, because when accuracy was evaluated the older adults also tended to produce fewer errors than younger adults (D. V. Howard & Howard, 1989, 1992). The majority of ASRT and TLT tasks find similar differences in RT and accuracy between age groups, with older adults responding more slowly but more accurately than younger adults do. This pattern can be manipulated: it disappears when feedback is provided to encourage participants to aim for a particular accuracy rate (e.g., Bennett et al., 2007). Unlike the original SRT, though, results from the ASRT (Dennis, Howard, & Howard, 2003; Feeney et al., 2002; D. V. Howard et al., 2004) and TLT (Forman-Alberti, Seaman, Howard, & Howard, 2014; J. H. Howard Jr. et al., 2008; Simon, Howard, & Howard, 2011; Simon, Vaidya, Howard, & Howard, 2012) usually indicate reduced learning in older adults as compared to younger adults.

The increased sensitivity of the ASRT to age effects is consistent with the predictions of the HBH, given the added noise from random elements interspersed between the target elements (contributing to memory interference) and the nonadjacency of the target elements (reducing the temporal proximity which the hypothesis suggests drives older adults to automatically bind items.) The TLT experiments listed here interleave patterned and random or high- and low-frequency patterned trials, meaning that they, too, are compatible with the HBH's predictions regarding the effects of added noise during the learning process. Since the ADH predicts age interactions with these tasks only if the SRT allows explicit processing, in which case it should show *larger* age effects than the ASRT or TLT, it cannot easily account for these findings. Since the only studies on aging effects of spatial co-occurrence in IL have been conducted using the contextual cueing task, it is impossible to know whether the regularity type or the task itself are responsible for the lack of observed age effects in contextual cueing as opposed to serial response tasks. Regardless, the HBH addresses these results more aptly than the ADH, as described in the previous section.

The alternation between "patterned" and "unpatterned" trials present in the ASRT provided inspiration for the first set of studies described below, which present object-context pairs that are either frequent or infrequent in random order. This presentation strategy avoids blocking and allows the target relationships (frequent pairings) to be presented alongside the nontarget relationships (infrequent pairings). A similar strategy is used for the second set of described studies, which also present target and nontarget stimuli in a semi-random intermixed order. The second set of studies also uses a triplet-based sequence, requiring responses only to the third member of the triplet, similar to the TLT; this reduces the motor and spatial demands of the task in the same way the TLT does, diminishing the chances that such demands drive any observed age effects. In this way, both sets of experiments borrow heavily from aspects of the ASRT and TLT as compared to the other IL tasks discussed here, and we expect that the interactions between the two AB models and our tasks should be similar to those discussed above.

1.3.2.2 **Covariation tasks.**

Contextual cueing. Sequential regularities are not the only type of information that can be learned and tested implicitly, however. Other research has focused on contextual cueing, which applies a visual search task to evaluate implicit learning of visual spatial information (Chun & Jiang, 1998). In a typical contextual cueing task, participants view a matrix of elements, one of which has been designated the target, and indicate the location of the target within the matrix (either the quadrant or its exact location). The arrangement of the other elements is associated with a particular target location; for example, matrix arrangement A might indicate that the target is in the upper right quadrant while matrix arrangement B might indicate the target is in the lower right quadrant. Participants' learning of these cues is tested by comparing the accuracy and speed of their responses on trials that use these deterministic arrangements to their responses on randomly determined arrangements. Experiments may be divided into training and testing phases, in which the training phase contains only patterned arrangements and the testing phase contains both patterned and random arrangements (e.g., Merrill, Conners, Roskos, Klinger, & Klinger, 2013), they may be divided into patterned and random blocks (e.g., Schmitter-Edgecombe & Nissley, 2002), or they may contain patterned and random arrangements interspersed throughout the experiment (e.g., J. H. Howard Jr., Howard, Dennis, Yankovich, & Vaidya, 2004).

Clearly, the contextual cueing task relies heavily on visual-spatial information. The complexity of the display and the required precision of the response can be reduced without promoting explicit learning of the regularity (Merrill et al., 2013), but even when the display is simplified the visual search task is much more perceptually complex than the SRT or AGL tasks. Additionally, unlike the SRT or AGL task, the order in which the participant encounters or considers the elements in a given matrix is irrelevant; it is the overall configuration that is important, not the relationships between individual elements. This means that the spatial regularities in the contextual cueing task lack a temporal component relevant to the sequential regularities underlying the AGL and SRT tasks.

The ADH does not differentiate between older adults' learning of associations between concurrently-presented items versus sequentially-presented items, but the HBH asserts that temporal proximity is an important part of older adults' associative binding process. Therefore, contextual cueing paradigms may eliminate the temporal distance account of higher-order structure effects, in effect ameliorating any age-related decrease in performance on more complex regularities. Additionally, while younger adults may ignore the positions of other elements when searching for the target element, older adults should fail to inhibit those elements and thus retain their positions more readily, potentially leading to a hyper-binding-based advantage in this type of task. The task does, however, also include a risk of increased distraction and/or interference inherent in presenting many items at once. Thus, the HBH's predictions are unclear: the increased interference may or may not cancel out the potential boost older adults should experience from hyper-binding.

Empirical findings. Howard et al. (2004) compared younger and older adults' performances on ASRT, a sequential learning task, to contextual cueing, a spatial co-occurrence task. In the contextual cueing task, participants viewed a twelve-element matrix consisting of eleven randomly rotated distractor letter Ls and one rotated target letter T. Participants were to locate the target and indicate which direction the letter was pointing. Twelve of these matrices were repeated once in each block throughout the experiment, while twelve novel matrices were randomly interspersed with the repeated displays in each block. Comparisons between the repeated and novel displays revealed that both groups showed significant learning effects on RT, and that there were not significant group differences in the magnitude of these effects. These results were consistent in both raw RT analyses and proportion-change analyses, suggesting that the learning effect in older participants was not inflated due to overall higher RT. The same participants who showed age-invariance in the contextual cueing task showed decreased learning effects on RT and accuracy on a four-element ASRT, indicating that task effects and not participant characteristics were responsible.

This result is compatible with the HBH, which predicts that the more temporally proximal two items are, the more likely they are to be bound by older adults, and that younger adults will ignore non-target items (a disadvantage during a contextual cueing task, which relies on non-target items to cue the position of the target) whereas older adults will not. This evidence indicates that the potential interference and/or distraction effects from presenting multiple items concurrently does not override these advantages for older adults. Since the ADH does not distinguish between concurrently- and sequentially-presented relationships, it is less compatible with this study's outcome. It is important to note that the first set of described studies uses a concurrent presentation of stimuli with fewer distractors than a traditional contextual cueing task, whereas the second set uses sequential stimulus presentation, so this interpretation of the HBH's predictions regarding simultaneous presentation could potentially be corroborated or refuted by their results.

1.3.3 **Summary**

Clearly, sequence and task considerations for the study of aging and IL are complex. These considerations reflect the broadness of the concept of "implicit learning," which can refer to a wide variety of learning behaviors that can be measured in a wide variety of ways. In general, the type and complexity of the target regularity and the nature of the task appear to affect older and younger adults differently, with some conditions showing age-equivalence (e.g., lower-order sequences, blocked testing conditions, and contextual cueing task demands) and others highlighting differences across age groups (e.g. higher-order sequences, alternating testing conditions, and sequential task demands.) Overall, it appears as though the HBH is better able to account for these task differences, but to date neither the ADH nor the HBH has ever been directly applied to these varying sequence and task characteristics in the literature. While none of the below-described studies aim to address this gap, the previously discussed evidence has been considered carefully during the design of the studies to choose an appropriate set of sequence characteristics and task characteristics, so that the results can be interpreted without concern that the tasks failed to address an important aspect of these concerns.

2.0 Domains of Cognitive Aging and their Implications for IL Performance

In a policy report on cognitive aging, the National Academy of Medicine outlined a definition of cognitive aging that includes the following areas: processing speed, memory, attention, executive function, spatial ability, intelligence, reasoning, language ability, and wisdom (Blazer, Yaffe, & Liverman, 2015). Of these nine facets of cognition, five have been proposed as theories to totally or partially explain the effect of aging on IL. In this section, I will summarize the evidence used to support those theories. Where relevant, I will explore how the AB account of age effects on IL and its two competing models interact with that evidence. This extensive literature review is intended to provide a thorough understanding of the existing literature, and the ways that each of the two competing models in question are consistent or inconsistent with the findings in that literature.

2.1 **Episodic Memory**

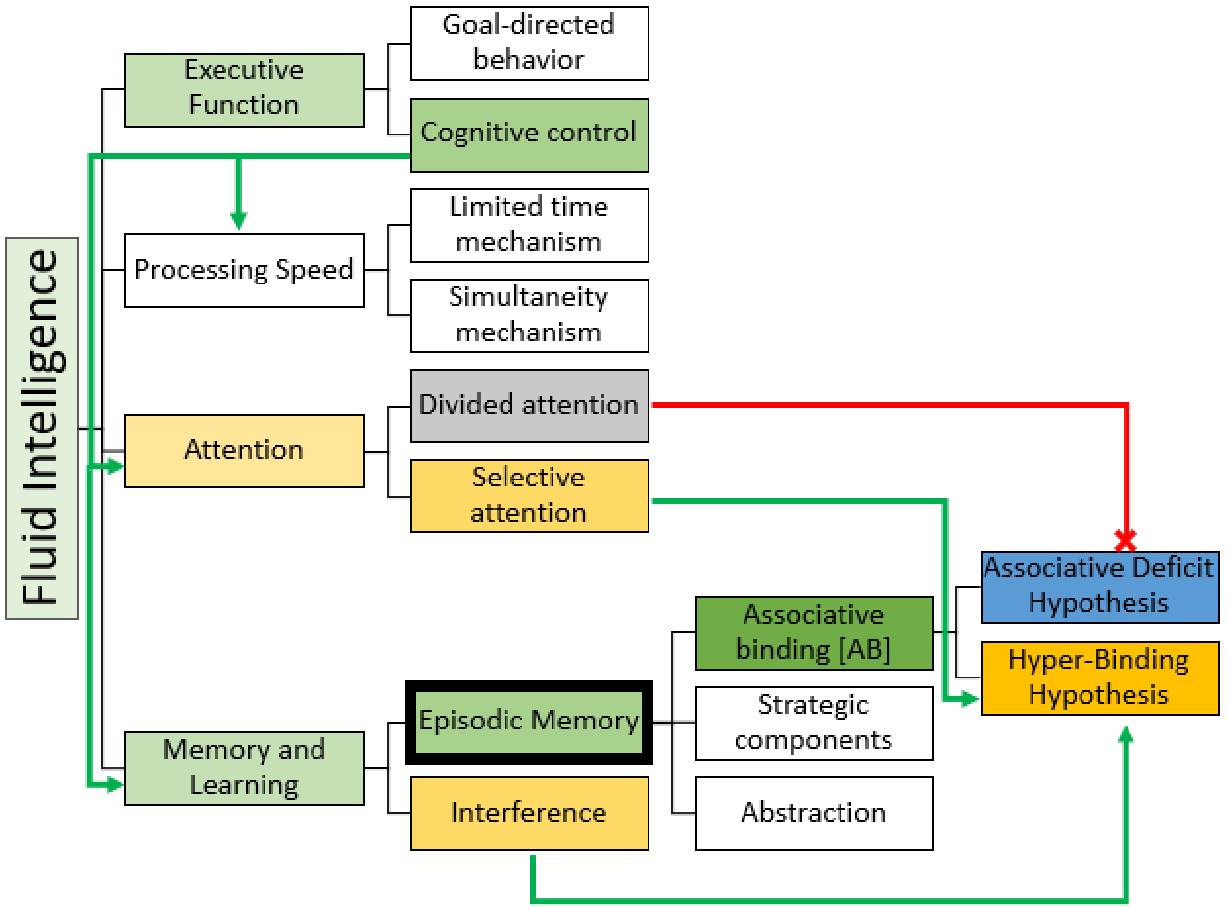

Figure 6: Hierarchy of memory and learning concepts, situated within broader cognitive context

Memory is a multifaceted system, some areas of which appear to be vulnerable to the aging process while others remain relatively unaffected (Blazer et al., 2015). In the broadest terms, memory is often characterized as consisting of multiple parts, including *working* and *long-term* subcomponents, the latter of which is further divided into *episodic* and *semantic* components (Blazer et al., 2015). Working memory is a complex and contentious topic, but it generally concerns the maintenance and manipulation of information as it is being used. In general, performance on working memory tasks declines with age. Semantic memory, or the long-term storage and retrieval of factual information without specific experiential associations, is usually spared during healthy cognitive aging (Laver, 2016). Although both of these memory systems can be important to learning, they have not been specifically studied in the context of aging effects in IL and thus are not a focus in the current literature review.

Episodic memory, or the long-term storage and retrieval of experiences (often referred to as "autobiographical knowledge," or knowledge that is tied to a specific event) is more affected by aging relative to semantic memory (Shing, 2016). Since AB concerns building associations based on experience, it is considered part of episodic memory by both the HBH and the ADH. Outside AB, other episodic memory-based explanations for age effects in IL involve strategic components of episodic memory as well as levels of abstraction in the stored representations. This section focuses on the observed evidence for all of these accounts: first, the AB-focused accounts, including the ADH and HBH; then, accounts based on other episodic phenomena, including strategic and abstractive differences.

2.1.1 **Associative binding.**

As stated earlier, AB -- the learning of relationships between informational units -- is the ultimate goal of IL tasks. One potential explanation for age differences in IL performance is that older adults experience some difference from younger adults in the process of acquiring, storing, or retrieving knowledge of associations, or in the products of those processes. The experiments described in this document test the predictions of two models of possible age-related differences in AB.

Before exploring these competing models, however, it is worth questioning whether AB is affected differently by cognitive aging than other types or mechanisms of episodic memory. Is it appropriate to focus on association rather than episodic memory as a whole? Evidence from Silver, Goodman, and Bilker (2012) suggests that associative memory is, in fact, distinct from logical memory, object-recognition memory, and memory related to executive functions. In this study, Silver and colleagues administered to groups of younger (aged 18-60 years) and older (aged 61-85 years) adults a battery of neuropsychological assessments. Among these, there were several tests of cognitive function in general and episodic memory in particular: the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) measured gross cognitive function; the Logical Memory subtest of the Wechsler Memory Scale-Revised (WMS-R; Wechsler & Stone, 1987) measured logical "item" memory; the Paired Associates-Easy and -Difficult subtests of the WMS-R measured memory for verbal associations; the Abstraction, Inhibition, and Working Memory Task (AIM; Glahn, Cannon, Gur, Ragland, & Gur, 2000) measured memory related to executive function; and the Visual Object Learning Test (VOLT; Glahn, Gur, Ragland, Censits, & Gur, 1997) assessed object recognition. Additional tasks measuring verbal working memory, spatial working memory, and psychomotor speed were also administered.

While the MMSE scores of the two groups were similar, older adults tended to score lower on the assessments than younger adults did. This was true for the Paired Associates tasks in particular; analysis of variance revealed that older adults' performance relative to younger adults on the associate task was significantly reduced compared to their relative performance on the AIM and the VOLT. The age gap in performance on the Logical Memory test was similar to that of the Paired Associates task, however. Stepwise regression analysis was performed to determine what types of factors drove the relationship between these two tasks, and it revealed that age and spatial working memory were much stronger predictors of Logical Memory performance than Paired Associates performance was. The correlation between associative and logical memory performance was greatly reduced when the analysis controlled for age and spatial working memory. Thus, this study demonstrates both that paired associate learning is more severely affected by aging than object recognition or executive function-related memory, and that it is at least partially independent of logical "item" memory as well. Given these results, it is appropriate to discuss associative memory separately from other types of episodic memory, although the relationship between memory for items and memory for associations should not be ignored. This motivates both the ADH, which argues directly for a dissociation between memory for associations versus items, and the HBH, which focuses on a dysregulated associative process that logically allows for such a dissociation.

Shing et al. (2010; 2008) model the subdivisions of episodic memory differently from Silver et al., proposing a two-part framework in which episodic memory is a combination of strategic and associative components. To test this framework, groups of children [YC], teenagers [OC], younger adults [YA], and older adults [OA] completed paired associate recognition tasks, where they studied word pairs and then completed a recognition task of either the items within the pairs or the pairs themselves. The difficulty of the association was modulated by either presenting both words in the participants' native language, or presenting one of the words in the pair in Malay. The strategic demand was manipulated by changing the instructions participants received before the study phase: they were told to remember the individual items (depending on *incidental* learning for pair recall), to remember the pairs of items (*explicit* learning of pairs), or to use an elaborative-imagery *strategy* to create and remember a mental image that connected the item pairs. Analysis of variance for the "easier" native-native word pairs revealed a main effect of age, such that YAs and OCs performed better than OAs and YCs on the pair recognition task. There was also an interaction between age and encoding instruction, such that *explicit* instructions improved OCs' and YAs' performance relative to *incidental* instructions on the pair recognition task more than it improved YCs' and OAs' performance. The *strategic* elaborative imagery instructions improved YAs' and OCs' performance relative to the pair-learning instructions, but this effect was smaller than the effect of *explicit* instructions compared to *implicit*. Further, the *strategic* instructions improved YCs' performance more than it improved OAs'. The age-instruction interaction was not present when participants studied the "difficult" native-Malay word pairs, although the main effect of age remained. This consistent main effect of age suggests that the associative component of episodic memory is reduced in YCs and OAs compared to OCs and YAs. The age-instruction interaction provides evidence for the strategic component and its changes across the lifespan: OCs and YAs improved their pair recognition performance most under explicit relative to incidental instructions, with the strategic instruction producing only a small additional improvement, suggesting that the OCs and YAs were already using self-initiated elaborations when learning pairs explicitly. Meanwhile, children required explicit prompting to use an episodic memory strategy, but they successfully improved their performance when they were cued, whereas older adults apparently did not use strategies successfully in any case. In sum: these results suggest that older adults may experience deficits to both strategic and associative components of episodic memory, but that these components are dissociable across the lifespan, further confirming that it is appropriate to explore an associative binding theory of age effects in IL as opposed to a general episodic memory theory.

So, assuming that AB behaviors change independently of other episodic memory functions as people age, what do those changes look like? The two models explored by the current experiments answer this question in competing ways. The primary distinction between the two accounts is the type and location of the difference: the ADH asserts that older adults are less likely to acquire and/or store associations, while the HBH asserts that older adults acquire and store *more* associations, leading to interference problems during retrieval. In the next two subsections, I will elaborate on the brief explanations of the two models given in the Introduction by reviewing in detail the evidence that has been used to support the competing hypotheses, and identifying the ways that the current research expands on this evidence.

2.1.1.1 **The Associative Deficit Hypothesis.** The ADH was first specifically tested in a series of experiments comparing memory for items to memory for relationships in younger and older adults (Naveh-Benjamin, 2000). Participants in all of the experiments studied index cards containing the stimuli: word-nonword pairs (Experiment 1), word-word pairs (Experiment 2), word-font combinations (Experiment 3), or word-word pairs in which the words were either related or unrelated to each other (Experiment 4). In Experiments 1-3, participants completed item and pair recognition tasks following the study phase; in Experiment 4, they completed free recall, cued recall, and item recognition tasks. The ADH asserts that older adults have a memory deficit that is specific to relationships and does not affect individual informational units; thus, Naveh-Benjamin predicted that older participants would perform poorly on the pair recognition tasks compared to younger adults, but that they would perform similarly to younger adults on the item recognition tasks. Further, given the associative task demands inherent in cued-recall, Naveh-Benjamin hypothesized that older adults would perform worse in the cued-recall condition as compared to the free recall and item recognition conditions.

Recognition tasks were analyzed using a corrected "hit rate" consisting of the number of correct identifications minus the number of incorrect identifications (or "false alarms.") In

Experiment 1, where participants learned word-nonword associations, ANOVA revealed an interaction between age and test, such that older adults were less accurate than younger adults at recognizing word-nonword pairs and at recognizing individual nonwords, but were equally accurate at recognizing words. Naveh-Benjamin accounts for the older adults' difficulty in recognizing nonwords by suggesting that, lacking prior experience with the nonwords, older adults found the individual letters of the nonword to be the most informative unit and tried to build associative relationships between those letters, rather than acquiring the entire nonword as a single unit.

Experiment 2 removed the word-nonword comparison by using word-word pairs and added an instructional manipulation: half of the participants were instructed to study and remember the individual words, while half were instructed to study and remember the pairs of words. ANOVA revealed an interaction between age and test, such that older adults performed much less accurately than younger adults on the pair recognition test, but this difference was smaller in the item recognition test. Further, the three-way interaction between age, test instruction, and test type was significant, such that the interaction between age and study instructions was absent in the item recognition test, but present in the pair recognition test such that the age difference was much larger when participants were instructed to remember the word pairs than when they were instructed to remember the individual words. Younger adults were much more accurate when instructed to remember pairs (M=.57) than when instructed to remember items (M=.35), whereas older adults did not show an effect of instruction (M=.16 in both conditions).

To explore whether relationships other than item-item follow a similar pattern, Experiment 3 paired items (words) with attributes (fonts), and participants were instructed to remember either the fonts, the words, or the word-font combinations. ANOVA again revealed an interaction between age and test, such that older adults were less accurate than younger adults in the word-font association recognition test, but performed equivalently in the word and font recognition tests. The three-way interaction between age, test, and study instructions was not significant.

Finally, Experiment 4 tested the effects of two types of support: first, the presence or absence of pre-existing relationships between items, and second, the type of environmental supports present during retrieval. Participants studied semantically related or unrelated word pairs, and performed cued-recall, free-recall, or item recognition tasks. Three-way ANOVA revealed an interaction between age and memory task, such that the negative effect of older age was largest in the cued-recall task (which requires associative memory,) smaller during free recall (which is aided by but does not require associative memory,) and smallest during item recognition (which does not require associative memory.) Age and pair type also interacted, such that older adults performed worse than younger adults on tests of unrelated pairs, but not on tests of related pairs. The three-way interaction approached significance ($p<.08$), indicating that age and memory task may have interacted for unrelated pairs but not for related pairs.

Overall, these experimental results indicate that older adults tend to show larger performance disadvantages compared to younger adults when a task requires learning of associations, rather than individual informational units, and that these performance disadvantages are exaggerated by intentional learning instructions but are present even in "incidental" learning conditions, where participants focus on individual items rather than their relationships. This supports an associative binding theory of age effects in IL. Further, the results suggest that when the units to be associated have a pre-existing relationship in the learner's memory, this age-related associative difference is reduced in both recall and recognition memory tasks. According to Naveh-Benjamin, the fact that existing associations show a smaller age effect is evidence that a reduced ability to form *new* associations may be the source of the age-related differences. In other words, where the AB theory suggests only that older adults experience some difference in the binding process or products, the ADH asserts that older adults have a specifically reduced capacity to form and/or store new associations. This is an important distinction, as some evidence that has been identified as supporting the ADH supports a general associative *difference* rather than this specific *deficit* in acquisition and storage.

In a later experiment, Bender et al. (2010) replicated Naveh-Benjamin's original Experiment 2 using a computerized version of the word-word pair learning paradigm to test a group of participants with a continuous range of ages, rather than the extreme age groups design used in the original study. These investigators removed the instructional manipulation: all participants were told to remember both the individual items and the pairs. A general linear model analysis revealed a significant interaction between age and test on recognition accuracy, such that advanced age was more negatively associated with accuracy on the pair recognition task than on the item recognition task. In other words, increased age led to supra-additively worse pair recognition relative to item recognition. This lends further evidence that age affects AB performance, and that this effect is not limited to an extreme-groups design. Analyses of "hit rate" and "false alarm rate" revealed a main effect of age, such that greater age was associated both with fewer true-positive identifications and more false-positive identifications. Age and test again interacted on both these measures, such that the age effect on true positives and false positives was stronger in the pair recognition test than the item recognition test. Response bias analysis confirmed a more liberal response criterion for older individuals. The authors argue that the error analysis and response bias could indicate that older adults rely more on familiarity than specific recall, although it could also reflect reduced inhibitory ability leading to noise during retrieval (the main argument of the HBH). Therefore, though this experiment is self-described as a test of the ADH, it only supports a general AB theory of age-related learning effects and not the specific deficit in associative acquisition and storage suggested by Naveh-Benjamin (2000).

Other research sought to further support a specific acquisition or storage deficit by ruling out effects of attentional differences. Naveh-Benjamin, Hussain, Guez, and Bar-On (2003) performed two experiments in which an older adult participant group (OFA) was compared to two younger adult groups: one that completed the task with full attention (YFA), and one that divided their attention (YDA) by completing a secondary digit-detection task. This secondary task consisted of listening to an audiotape that played a series of digits read aloud once every second, and producing a verbal indication when three consecutive odd digits were read. The YDA group was instructed to pay equal attention to this secondary task and the primary associative learning task, while the OFA and YFA groups did not encounter the secondary task and were instructed simply to learn the item pairs in the primary task. As in the experiments from the Naveh-Benjamin (2000) paper, participants studied pairs of items and then completed item and pair recognition tasks. In Experiment 1 of this study, the items were drawings of objects, and in Experiment 2 they were pairs of either related or unrelated words. Separate analyses of variance of the accuracy data from the younger and older groups in Experiment 1 revealed an interaction between age and test, such that OFAs performed worse relative to both YFAs' and YDAs' performance on the pair recognition test than they did on the item recognition test. No such interaction between group and test existed when the YDAs' performance was compared to the YFAs'. These results indicate that, while older adults showed a selective disadvantage on the pair recognition task compared to younger controls, younger adults performing a divided attention task did not reproduce this pattern. Experiment 2 revealed similar results regarding the effects of divided attention: ANOVAs of both the OFA-to-YFA comparison and the OFA-to-YDA comparison found significant three-way interactions between group, test, and pair relatedness, such that older adults again performed selectively poorly on the pair recognition test compared to the item recognition test relative to younger adults when word pairs were unrelated. When the word pairs were related, however, this selective associative deficit was not exhibited by the older group. The YFA-to-YDA comparison revealed no significant interactions, again disconfirming a selective associative deficit induced by divided attention.

A second investigation into the possibility of divided attention as a way of inducing an associative deficit (Naveh-Benjamin, Guez, & Shulman, 2004) replicated Experiment 2 from the 2000 study – participants studied unrelated word pairs, and performed item- and pair-recognition tasks. The attentional manipulation in the younger adults was within-subjects, rather than between-subjects as in the 2003 study. Analyses of variance again found an interaction between age and test for both attentional conditions – regardless of whether the younger adults were in the full- or divided-attention condition, older adults showed supra-additively lower performance on the pair recognition test than on the item recognition test when compared to the younger adults' performance. ANOVA of the two attentional conditions in the young adults did not show an interaction between attention and test, meaning that younger adults showed the same performance on the pair recognition task relative to the item recognition task regardless of whether their attention was divided.

A final pair of experiments (Kilb & Naveh-Benjamin, 2007) examined the effects of divided attention on *both* older and younger adults' performance. The authors argued that if limitations to attentional resources are responsible for the age-related associative disadvantage, then adding additional attentional demands should exacerbate the established age-test interactions observed in previous studies. The attentional manipulation was within-subjects, meaning all participants completed both a full-attention and a divided-attention version of the protocol. In the divided-attention condition, participants were instructed to pay equal attention to the secondary and primary tasks. In the secondary task, participants indicated whether a tone was low, medium, or high by pressing a key on a computer keyboard while they completed the study portion of the primary task. Each time the participant responded, the next tone was played. In the primary associative learning task, participants studied unrelated word pairs and completed item- and pair-recognition tests. In Experiment 1, participants were instructed to learn both the items and the pairs in preparation for the recognition tasks. In Experiment 2, in an attempt to reduce the attentional demands of the primary task, participants were only instructed to learn one of these – either the items or the pairs – and completed only the corresponding test.

A two-way ANOVA of the age and test effects in the full attention condition of Experiment 1 revealed an interaction of age and test such that older adults performed similarly to younger adults on the item recognition task, but worse than younger adults on the pair recognition task. In the divided attention condition, this interaction was not significant. A two-way ANOVA of test and attention effects within the older adults revealed an interaction such that the difference between the item and pair recognition tasks was smaller under divided attention than it was under full attention. For Experiment 2, the two-way interaction between age and test under full attention was again significant such that the age effect was absent on the item test but present for the pair test. Neither the older nor the younger group showed a two-way interaction between attention and test type. Finally, analysis of older adults' performance on the secondary task revealed no effect of study instructions (either pairs or items) for either age group – suggesting that older adults did not experience a larger attentional load when attending to pairs as opposed to individual items.

This body of evidence shows that dividing attentional resources in younger individuals does not cause them to exhibit the selective associative disadvantages observed in older adults, and dividing attention in older adults does not exacerbate these disadvantages. Although the authors argue that this is evidence against any attentional account of associative differences in aging, such a conclusion is suspect. Divided attention, or "the ability to split one's focus between competing activities," (Blazer et al., 2015, p. 36), is only one aspect of attention that can be affected by aging. The HBH uses decreased selective attention – "the ability to filter information and focus on select items despite the presence of other information," (Blazer et al., 2015, p. 36) – to explain age-related differences in the outcome of AB tasks. Therefore, while this evidence does show that the type of attentional control that was specifically tested is unlikely to be responsible for the age-related associative difference, it does not rule out other types of attentional control as possible mechanisms.

The 2003 study does, however, support one facet of the ADH, in that the related word pairs did not show the same age-related associative disadvantage as the unrelated word pairs. The ADH's claim that this is because older adults struggle to form new associations, but can access existing relationships, is a plausible interpretation of this pattern of data. Therefore, while these studies do not accomplish the goal of ruling out attention-based accounts of associative differences in aging, they do lend further support to one of the core arguments of the ADH, that aging may affect learning of associative relationships.

2.1.1.2 **The Hyper-Binding Hypothesis.** Campbell, Hasher, and Thomas (2010) approached the question of adult age differences in AB from a different perspective, citing previous evidence that the “bandwidth of attention” (Campbell et al., 2010, p. 399) increases with age due to a decline in inhibition, making older adults more susceptible to distraction during cognitive tasks (e.g. Lynn Hasher & Zacks, 1988; Lustig et al., 2006) and prospective interference during memory tasks (e.g. Biss, Campbell, & Hasher, 2013). To test this hypothesis, the authors conducted a series of two experiments testing participants’ memory for attended and unattended relationships in a set of stimuli. In both experiments, groups of younger (aged 17-29 years) and older (aged 60-75 years) adults first completed an n-back task on a series of line drawings. In the n-back task, participants are presented with a string of stimuli, and are instructed to respond when they see a repetition of the stimulus that was *n* trials before it in the sequence. In this experiment, the participants performed an adapted 1-back task in which the target line drawings had irrelevant words superimposed on them, and participants were instructed to ignore these words. Unknown to the participants, a subset of the pictures was consistently paired with the same word every time the participants saw them. Following a delay, the participants then completed a paired-associates learning task where they learned word-picture pairs, some of which were the intact consistent pairs from the n-back task, some of which were recombined words and pictures from that task, and (in Experiment 1) the rest of which were entirely novel to the participants. After studying the picture-word pairs, participants completed a cued-recall test where they were shown the picture and asked to produce the appropriate word.

In Experiment 1, analyses of variance revealed an interaction of age and pair type on recall accuracy, such that older adults performed better on preserved pairs than they did on novel pairs, and worse on recombined pairs than on novel pairs, whereas younger adults did not perform differently across pair types. To rule out the possibility that older adults were relying on explicit memory of the picture-word pairs from the n-back task, additional younger and older control groups completed the n-back task and then (without completing the paired-associates study phase) performed cued recall and associative matching tasks, on which none of the participants performed above chance. Experiment 2, which removed the novel pair condition during the cued-recall task, revealed a similar interaction between age and pair type, such that older adults performed significantly better on the preserved pairs than the disrupted pairs, but younger adults performed relatively equivalently irrespective of pair type. In both experiments, older adults were slower and less accurate during the n-back task, which may indicate that they were more distracted by the superimposed words than the younger participants. The results from these two experiments suggest that older adults may attend to relationships younger adults ignore, and that this reduction in attentional regulation leads to participants forming too many associations resulting in interference during retrieval. In other words, the differences in associative memory observed in older adults are caused by inefficient filtering during acquisition, not by a specific deficit in the formation of the associations themselves.

To further explore this idea, Campbell et al. investigated whether or not older adults learn implicitly from unattended or "irrelevant" information when it is not presented simultaneously with the attended information. The researchers again used the n-back task to provide a source of implicit associative learning. The stimuli were two sequences of line drawings, colored green and red respectively. These sequences were constructed by arranging triplets of pictures in a pseudorandom order, and repeating the last picture of some triplets (e.g., ABC/GHII/DEF/ABCC/JKL). The pictures from the two sequences were then interleaved, and participants were instructed to attend only to one of the colored sets while ignoring the other. Participants were not made aware that the pictures were presented in a pattern.

Following training, participants' implicit knowledge of the pattern in each sequence (attended and unattended) was tested using a speeded detection task. Participants were shown a picture from the sequence and were instructed to look for that target in a series of 18 rapidly-presented pictures. The set of 18 pictures followed the training sequence from the n-back task; implicit learning was measured by the reaction time difference between pictures that came first in triplets and those that came later; since the second and third pictures in the triplet were deterministically predictable by the first, knowledge of the sequence should allow participants to anticipate a late target, but the first target in each triplet could not be anticipated.

ANOVA of response times at Position 3 in the tested triplets (the position where pattern learning would facilitate responses the most) revealed an interaction of stream attendance and age, such that younger adults responded faster to items from the attended stream compared to those from the unattended stream, while older adults responded with similar speed regardless of stream attendance. In other words, younger adults showed a larger effect of learning in the testing phase on the sequence they attended to during the learning phase compared to the unattended sequence, but older adults showed similar learning effects for both the attended and the unattended sequences. These results again suggest that older adults may fail to inhibit the formation of associations in irrelevant stimuli.

These prior experiments demonstrate instances of positive interference between irrelevant and task stimuli for older adults; the tasks were designed such that memory of the irrelevant relationships during the initial n-back tasks improved performance on the subsequent associative memory tasks. The HBH asserts, however, that the interference from these irrelevant relationships should also cause poorer performance in tasks that are not designed to capitalize on knowledge of those relationships. To test this prediction, Biss, Campbell, and Hasher (2013) replicated

Experiment 1 from the original 2010 study, in which participants performed an n-back task on pictures with irrelevant superimposed words and then performed a paired-associates learning task on pairs of words and pictures. In the original study, the paired-associates task included intact pairs, recombined pairs, and novel pairs; in the 2013 replication, some participants were tested only on entirely novel pairs (low-interference condition,) whereas others were tested on a combination of recombined and novel pairs (high-interference condition.) The authors argued that the recombined pairs should induce more interference during retrieval than the novel pairs, since the participants would have previously-stored associations for these items that did not match the ones they were learning in the paired-associates task. This argument was supported by an ANOVA of the participants' response accuracy during the cued-recall portion of the paired associates task, which revealed an interaction between age and interference level such that younger participants were equally accurate across the low- and high-interference conditions, whereas older individuals were more accurate in the low-interference condition as opposed to the high-interference condition. Critically, the older adults were less accurate even on the novel pairs they encountered in the high-interference condition, suggesting that the presence of the recombined stimuli led to interference that "overwhelm[ed] older adults' memory in a similar manner as other item-non-specific interference effects," (Biss et al., 2013, p. 560).

To further explore the temporal characteristics of negative interference stemming from hyper-binding, Campbell, Trelle, and Hasher (2014) conducted a series of experiments that compared interference effects on younger and older adults of items presented in either near or far temporal proximity. Similar to a standard paired-associates task, in each experiment participants studied a list of semantically-unrelated word pairs in preparation for a recognition task, where they distinguished intact pairs from rearranged pairs. The word pairs were presented for study one at a time, with each pair visible for two (Experiments 1a and 2) or four (Experiment 1b) seconds. The recombined pairs in the recognition task were constructed by using the cue term from one pair and combining it with either a near neighbor (the associate word from the following pair in the study list) or a far neighbor (the associate word from the pair nine items later in the study list). In Experiments 1a and 1b, participants encountered either the near- or the far-rearranged pairs during the recognition task; in Experiment 2, participants encountered both types of rearranged pairs. The authors expected younger adults to learn only the target within-pair relationships, but older adults to bind items across pairs as well, leading to memory interference when near neighbors were presented.

Experiment 1a was analyzed with a two-factor between-subjects ANOVA, which revealed an interaction between age group and rearranged pair type, such that older adults who saw near-rearranged pairs made more “false alarm” errors than older adults who saw far-rearranged pairs, whereas younger adults made a similar number of errors regardless of the distance of the rearranged pairs. ANOVA of correct identifications (“hits”) revealed no significant main or interaction effects of age and pair type. Experiment 1b was performed only on older adults, to ensure that the relatively short presentation time of the pairs during the study phase was not responsible for the older adults’ performance patterns during Experiment 1a. T-tests revealed that these older adults also did not change in their “hit” accuracy across pair types, but did commit more “false alarm” errors when they saw near-rearranged pairs than when they saw far-rearranged pairs, confirming that longer study times did not ameliorate the interference effect for older adults. Finally, Experiment 2 was evaluated using two-way mixed-factor ANOVA, with age as a between-subjects factor and pair type as a within-subjects factor. Again, the critical interaction between age and pair type on false alarm rates was significant, reflecting older adults’ higher tendency to make more of these errors on near-rearranged pairs than on far-rearranged pairs while younger adults' error rates are unaffected by pair type. Hit rate was unaffected by group. These results indicate that, in the explicit paired-associates paradigm favored by researchers of the ADH, older adults still attend to relationships that younger adults inhibit, causing memory interference that increases false alarm errors and decreases adjusted accuracy.

2.1.2 **Other models based on episodic memory.**

Fandakova, Shing, and Lindenberger (2013) investigated whether the HBH model of associative changes in aging are compounded by other changes in episodic memory as a whole. Using the two-component model of episodic memory, in which associative components are complemented by strategic components, Fandakova et al. suggested that changes in memory monitoring processes might interact with dysregulated AB to foment false feelings of recognition in aging adults. To test this claim, the authors used a modified continuous recognition [CR] task, where participants viewed lists of word pairs one pair at a time on a computer screen, and indicated whether each pair was "new" (had not been seen before in the current experimental block) or "old" (had appeared previously in the current block). Participants rated their confidence in each response by indicating whether they were "sure" or "unsure." Before beginning the CR task, participants completed a familiarization task where they viewed a large set of word pairs one pair at a time and indicated whether one, both, or none of the words in the pair described an animate object. For each of the three blocks of the CR task, a subset of these familiarized pairs were selected to be "targets" that repeated once within the block ("old" pairs); another subset was selected to be "intact lures," which appeared only once in the block but had been encountered before during the familiarization task and potentially also in a previous block (familiar but "new" pairs), and a final subset was selected to form "rearranged lures," which also appeared once in every block and were made by pairing the left word from a target pair with the right word from a different pair (also "new" pairs, but the associations within them should be learned with repeated exposure making them less tempting over time). Finally, a set of completely novel pairs that shared no words with the familiarization set or any previous blocks were included in each block of the CR task.

Linear growth models revealed that both younger and older adults committed false alarm errors on intact lures more often as the experiment progressed, and that older adults' rate of these errors increased more rapidly than younger adults did, indicating that older adults were less able to inhibit memories from previous blocks than younger adults. Additionally, participants committed fewer false alarm errors on recombined lures as the experiment progressed, indicating that they learned the identity of those pairs and knew to avoid them with repeated exposure. This effect was smaller for older than for younger individuals. Finally, correct identification of targets did not change for either group over the course of the experiment. Critically, analysis of participants' confidence in their answers found that older adults were more confident in their false alarm errors on both intact and recombined lures than younger adults were over the course of the experiment, but younger adults were more confident than older adults in their correct identifications of targets. Younger adults became increasingly uncertain about their correct responses over the course of the experiment, and older adults' certainty decreased less rapidly than younger adults' did. Taken together, these results suggest that older adults are more likely to experience interference during memory tasks, are less likely to use specific memories of associations to inhibit tempting distractors, and are less successful at monitoring their memories to distinguish between familiarity and recognition. The authors argue that this evidence supports viewing associative memory within the two-component framework to get a full understanding of age-related changes in episodic memory performance. While this may be true, it is critical to first model how associative memory changes over time before its interaction with strategic components of episodic memory (like memory monitoring) can be fully understood. The fact that Fandakova et al. cite only the ADH in their discussion of age-related changes in associative memory, despite the obvious utility of the HBH in exploring the roles of interference and inhibition in the CR task, suggests a need for further exploration of how the two models would fit differently into the framework they propose.

Naveh-Benjamin, Keshet Brav, and Levy (2007) examined the interaction between associative and strategic memory components as well, at both encoding and retrieval. They approached the experiment from the perspective of the ADH, although they did not make the critical semantically related/unrelated comparison that supports the ADH specifically as opposed to a more general theory of age-related associative differences. In this study, three younger (aged 21-28 years) and three older (aged 65-83 years) groups of participants studied pairs of words one pair at a time, and were instructed to remember both the individual items and the pairs in preparation for item and pair recognition tasks. One group from each age level was also instructed to meaningfully relate the two members of each pair during study by creating a sentence linking them together. Another group from each age level was told to use this strategy during encoding, and further instructed to try to recall the sentences during the pair recognition task.

Participants' accuracy (measured as proportion of hits minus the proportion of false alarm errors) was analyzed using a mixed-effects ANOVA, with age and strategy instruction as between-subjects factors and test (item or pair) as a within-subjects factor. Unsurprisingly, main effects of age and test were significant, with younger participants outperforming older participants and the item test eliciting better performance than the pair test. The main effect of strategy instruction was also significant, with the basic instructions resulting in the worst performance, strategy instruction at encoding resulting in better performance, and strategy instruction at both encoding and retrieval resulting in the best performance. The interaction of age and test was significant, indicating that older adults performed at levels closer to younger adults' during the item test than during the pair test. There was also an interaction between age and strategy instruction, such that older adults showed greater improvement in response to strategy instructions (both at encoding and at encoding and retrieval) relative to their performance for the basic instructions than younger adults did. Finally, the three-way interaction between age, strategy instruction, and test was such that in the basic instruction condition, the age-by-test interaction was significant, but in the strategy instruction conditions the age-by-test interaction was not significant. In other words, when older adults received instructions to use a metamemory strategy, they showed a main effect of test type that was similar to young adults. Since the experiment did not specifically test the ADH, these results support only a general conclusion that strategic components of episodic memory may interact with associative components to exacerbate or alleviate age differences in memory performance, depending on task conditions. Again, without knowing the types of changes that drive age-related associative differences, it is difficult to make specific predictions about how and why the associative and strategic components should interact. It is also important to note that this study focused on conscious, effortful implementation of metamemory strategies, which is only one type of strategic process within episodic memory, and one that is unlikely to take place during IL.

An examination of more general issues in episodic memory was performed by Kürten, et al. (2012), who distinguished between instance-based memory of "chunks" and abstracted memories of "rules." Participants completed a battery of tests, including assessments of working memory and episodic memory, which confirmed that younger participants displayed superior episodic memory skill compared to older individuals. The participants then performed a standard AGL task, wherein they retyped strings of letters, were informed that those strings followed a predetermined sequence, and then classified new strings as either grammatical or not. The training strings contained some two- and three-letter sequences (called "chunks") that were common, and some that were not. During the test phase, the stimuli either followed the same structure as the training stimuli or did not, and they contained either the high- or the low-frequency "chunks." Correctly responding to the grammaticality of the string was considered evidence of "pattern-based" learning, while responding to the frequency of the chunks was considered evidence of instance-based or episodic learning.

The older subjects tended to respond inaccurately during the retyping phase when compared to the younger subjects. Regression analysis found that performance on standard measures of working memory capacity partially accounted for the variance in accuracy on this task. In the classification phase, all participants were more likely to endorse grammatical strings with high frequency chunks than grammatical strings with low-frequency chunks; analysis of variance did not find an effect of age. Planned comparisons revealed that the two age groups showed equivalent endorsement rates for strings with low-frequency chunks regardless of grammaticality, as well as ungrammatical strings with high-frequency chunks, but younger adults successfully identified grammatical strings with high frequency chunks more often than older adults did. The authors interpret these results as being indicative of explicit (frequency-based) versus implicit (pattern-based) learning differences: younger participants, who tend to be better at explicit learning tasks, learned the high-frequency “chunks” explicitly, while older participants, who tend to be worse at explicit learning tasks, did not. Some alternative interpretations are possible: it may be that older adults are less successful at generating abstract rule representations from groups of instances, and this age difference is only apparent when younger adults have a high level of exposure to instances and have strengthened their rule representations. It is also possible that, as the HBH might predict, older adults experience more interference from the high frequency chunks, leading them to be less successful at identifying the grammatical sequences; this interpretation is counter to the results from Fandakova et al., however, as they indicate that interference tends to make older adults more likely to endorse items, not less likely.

These results resemble the findings from an analysis of ASRT performance (J. H. Howard & Howard, 1997). In this experiment, participants' speed and accuracy of response were examined on trial triplets beginning and ending with random elements that mimicked triplets beginning and ending with sequence-based elements. In other words, the experimenters examined performance on trials within the sequence compared to trials that only resembled the sequence. While both older and younger participants showed a "boost" to these sequence-like triplets, only younger participants showed higher-order learning as determined by better performance on sequence triplets than on sequence-like triplets.

This pattern of results may seem counter-intuitive to an episodic deficit interpretation at first: if older adults are worse at instance-based learning, why would they show improved performance on sequence-like trials compared to trials unlike the sequence? A possible explanation is that younger adults experience a combined effect of implicit learning and episodic memory, which boosts overall performance and facilitates the learning of higher-order sequences compared to older individuals. If this is the case, then individual differences analysis should reveal a covariation of participants' episodic memory performance and their sequence-specific learning. Surprisingly, Kürten and colleagues did not evaluate the relationship between participants' scores on episodic memory tasks and their performance on the classification task; an analysis of these data on the level of individual differences could support or refute this episodic-memory-based interpretation. Of course, this more general approach to episodic memory as the capacity to remember encountered instances of stimuli incorporates within it the age-related AB theory; the potential interaction between the instance-based associative ability and abstraction of rules is complementary to the questions explored by the current studies.

Overall, issues of episodic memory are central both to the AB models being tested in the current studies and to the question of age effects on IL in general. In addition to the AB-specific behaviors being tested in the current studies, there is significant evidence that the strategic component of episodic memory can modulate the success of IL (Fandakova et al.) and that targeting strategic behaviors may ameliorate age-related AB difficulties (Naveh-Benjamin et al., 2007). Additionally, the process of abstracting from the stored “chunks” developed during AB to “rules” may differ across age groups (Kürten et al., 2012), suggesting that age differences in AB may be further complicated by these age differences in abstraction. These AB-related episodic phenomena are important to keep in mind while interpreting the results of the current studies, and provide important questions for future experiments.

2.2 **Attention**

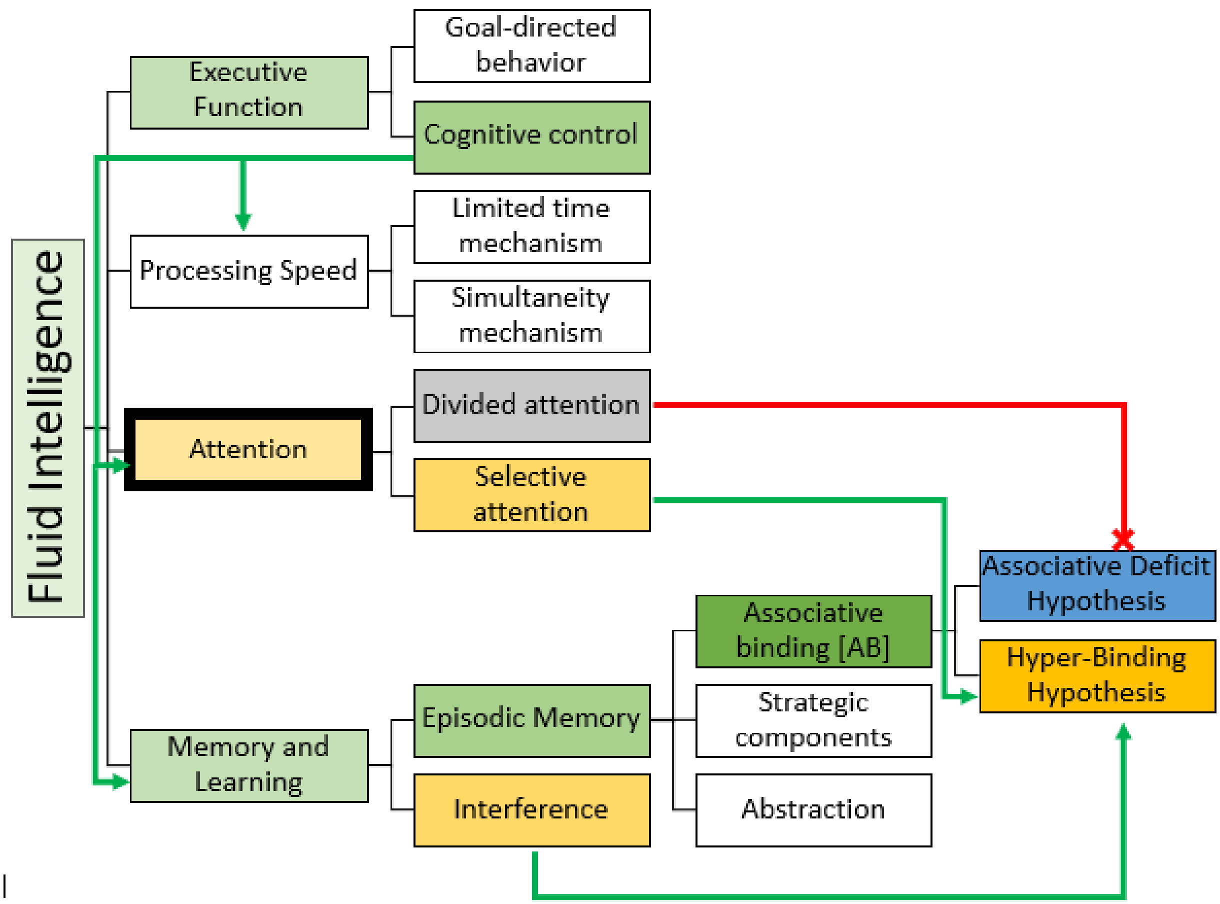

Figure 7: Hierarchy of attentional concepts, situated within broader cognitive context

2.2.1 **Selective attention.**

Like memory, attention can be subdivided into multiple capacities. Selective attention, which requires the individual to attend some information while inhibiting others, is known to decline with age (Blazer et al., 2015). The HBH depends on older individuals' reduced capacity for selective attention, but it focuses on the ways that this reduced capacity interacts with memory interference to affect older adults' associative memory performance. Therefore, although the investigations of the HBH are by nature also investigations of the interaction between selective attention and age on IL performance, I have chosen to classify them as associative memory investigations as the associative memory effects are the phenomena of interest during IL.

2.2.2 **Divided attention.**

Naveh-Benjamin and colleagues demonstrated that divided attention does not replicate age-related associative differences in younger individuals, nor does it exacerbate these differences in older adults (see previous section). That being established, there is some evidence that older adults are affected differently by division of attention than younger adults during IL. Nejati et al. (2008b) investigated the effects of divided attention on implicit learning across age groups. Participants completed a dual-task implementation of the SRT. They counted either high or low tones, one of which was randomly played in conjunction with each trial, while completing the traditional SRT task. Younger participants showed a learning effect on both accuracy and RT in the presence of this secondary task, whereas older individuals did not show facilitation during sequenced trials on either measure. This lack of a learning effect could be the result of attentional deficits, increased memory load, or both. The researchers attribute this lack of a learning effect in elderly participants to the fact that the dual task requires a division of attention, a capacity known to be reduced in older participants. Also possible, however, is that the memory demands of rehearsing the desired tone and maintaining its count left reduced "room" in the memory system for the target sequence.

This memory-loading interpretation was tested by Vandenbossche and colleagues (2014). These researchers re-created the dual-task study conducted by Nejati et al., but assigned participants different secondary counting tasks. Some participants counted tones, as in the original experiment, but others counted shapes presented in between trials. This change was intended to manipulate amount of memory interference of secondary task: if memory demands were the primary cause of the dual-task effect, then a secondary task involving visual stimuli should interfere more with learning of the visual-spatial sequence than the secondary task involving auditory stimuli. Younger participants did not show a difference between the single-task, dual-tone, and dual-shape conditions in terms of learning effects on RT. Older participants did not show a learning effect in either dual-task condition, as in Nejati et al., but they did show a learning effect in the single-task condition. Critically, older participants did not show a difference in learning performance between the two types of dual-task condition. These results suggest that the dual-task effects observed in older individuals are likely not due to differences in memory capacity or memory loading, but rather to either attentional capacity loading or attentional control.

It is important to note that this type of dual-task manipulation differs from the dual stimulus stream used in HBH studies in one critical aspect: while dual tasks require participants to attend to both streams to succeed, the HBH studies specifically instruct participants *not* to attend to the secondary stream of information. In other words, the most successful participants in a dual-task condition will be able to switch their attention rapidly between two tasks, whereas the most successful participants in the first portion of an HBH study will be able to completely ignore one task while focusing complete attention on the other. The HBH hinges on the idea that people who are less successful at the initial dual-stream task, which is aided by successful inhibition of the distracting secondary stimuli, might be facilitated in a subsequent task that then uses the previously-distracting stimuli as targets.

To date, no experiment has tested whether dual task effects on the primary, serial reaction time task persist in aged individuals when the secondary task is discontinued. Evidence suggests that the dual-task effect in younger individuals primarily reflects an interruption in task performance, rather than a disruption of sequence learning: participants who complete different numbers of blocks under single- and dual-task conditions show similar ultimate learning effects (Frensch, Lin, & Buchner, 1998), suggesting that dual-task conditions do not affect the amount of learning but only the expression of learning. Since dual-task conditions appear to affect older individuals disproportionately, it cannot be assumed that the same is true for this population. Assuming a dual-task condition incorporates more stimuli, the HBH might predict that older adults would experience more interference and thus show decreased ultimate learning effects, not just performance effects. The ADH, being less intrinsically linked to attention than the HBH, should not make any strong predictions regarding the effects of dual-task conditions on IL in older adults. In the absence of this comparison, neither model emerges as particularly supported or refuted by the existing evidence from divided attention studies. Although the current studies do not directly address this question, it provides an interesting direction for future investigations.

2.3 Executive function

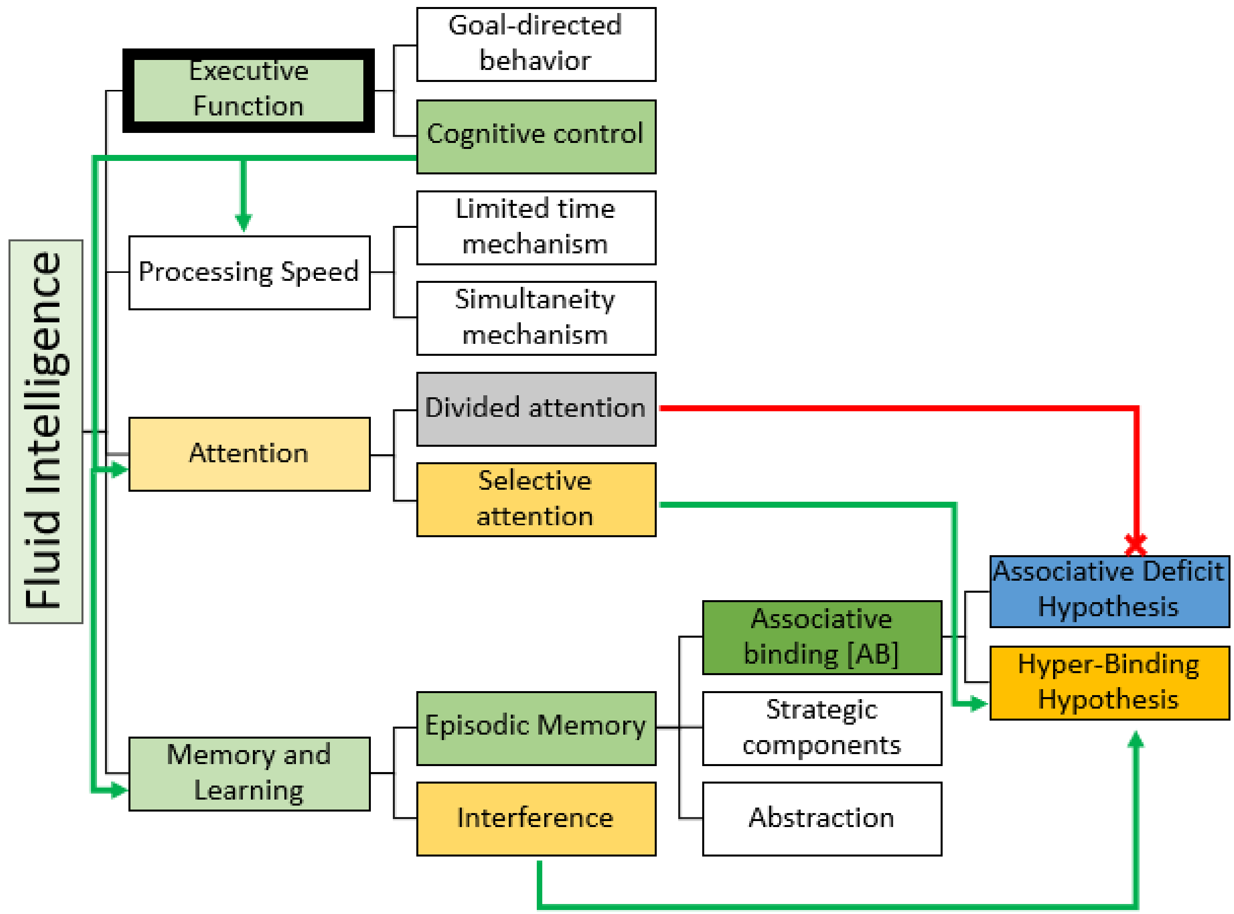

Figure 8: Hierarchy of executive function concepts, situated within broader cognitive context

As defined by the National Academy of Medicine, executive functions are "the cognitive skills used to regulate behavior and modify responses based on environmental cues," (Blazer et al., 2015, p. 39). This set of skills encompasses many of the previously discussed areas of cognition, including the allocation and inhibition of attention and memory. Indeed, the results regarding dual-task effects, attributed to the demands of attentional switching by the authors, could also be attributed to a decline in control abilities in general. A similar argument could be made for the HBH: if decreased selective attention is reflective of more general inhibition deficiencies, which seems likely when combined with the increased interference effects that are also critical to this model, it may make more sense to talk about the HBH in terms of 'cognitive control' rather than separate influences of attention and interference. This interpretation may be corroborated by evidence from explicit/implicit instruction comparisons across age groups: task instructions are a way of modifying participants' "top-down" cognitive control behaviors, so differences in the effects of instructions across age groups would suggest differences in those control behaviors.

Park and Shaw (1992) found differences in the way that younger and older adults' learning behaviors are affected by changes in instructions. Participants received a list of words at the beginning of the experiment and either counted specific letters in the words or rated the words on perceived pleasantness. After filler activities, participants received two- to four-letter word stems to complete, and were either instructed to use the words from the first task or were simply told to complete the words without specific instruction regarding the earlier task. Older adults produced the target completions less often than younger adults did when they had received the explicit instructions, but no age difference was observed in the implicit condition.

This study is more an examination of explicit and implicit *memory* than *learning*, given that both the ADH and the HBH would consider this an instance of item learning rather than associative learning. That being said, the results are somewhat surprising given the strategy-use evidence provided by Naveh-Benjamin et al. (2007): provided with an explicit cue to use a memory strategy, the older participants' performance decreased compared to younger participants; this is in direct contrast with the results found by Naveh-Benjamin and colleagues. The results do correspond well to the original 2000 study by Naveh-Benjamin, however, in the sense that younger adults benefitted from intentional instructions whereas older adults did not. The HBH might account for these results in a similar manner, by predicting that older adults would be less able than younger adults to inhibit interference from word knowledge outside the previously-encountered list, but that when younger adults were not attempting to focus on a specific set of words that difference would not be apparent.

A later study found similar effects in sequential learning. Verneau (2014) used a standard ASRT task, wherein some participants were informed that the trials followed an alternating sequenced-random pattern, and were given the details of the sequence, while the other participants were not informed that the trials followed a pattern. The results showed that younger participants benefitted from explicit instructions, while older participants did not. In a follow-up study, the time between the participants' correct responses and the presentation of the next stimulus was increased. Some, but not all, older adults were able to use the explicit information in this lower time restraint, but the effects did not transfer once stricter time restraints were introduced. Similar findings are described by Howard and Howard (2001b): not only were older participants unable to use explicit instructions to their advantage, they were actually disadvantaged by intentional learning. Midford and Kirsner (2005) provide further evidence for a selective disadvantage of explicit instructions on older individuals: in an AGL task, older participants performed equivalently to younger adults with incidental instructions, but performed much worse when provided with information about the grammar. Meanwhile, younger adults' performance improved under the explicit instructions.

These results suggest that, while younger participants successfully use explicit instructions to control their performance on sequential learning tasks, older participants are less able to do so, and may in fact be negatively affected by explicit instructions (c.f. Rieckmann & Bäckman, 2009). Song et al. (2009) argue, however, that this pattern reflects performance effects rather than true negative effects on participants' ability to acquire knowledge of the target sequence. In a modification of ASRT, the researchers introduced cued epochs at the beginning of each of the three training sessions, wherein patterned trials appeared in gray and random trials were in black, in order to facilitate explicit recognition of the pattern. The final epoch in each session contained all-black stimuli. The participants, who were all aged adults, received either intentional or incidental instructions. The majority of older adults given the intentional instructions explicitly learned the pattern, though a small number did not. Those who learned the pattern achieved higher scores on a standard WM task than those who did not. No participants in the intentional group of any age reported being aware of the pattern during the all-black probe epochs, suggesting that the effects of explicit learning created during the cued epochs did not transfer to the probe epochs. Analysis of these probe epochs revealed no RT differences between intentional and incidental groups in performance: both groups showed significant facilitation of patterned trials over random trials, a decrease in RT over time and training, and an increase in pattern-based RT facilitation over time. During the cued epochs, however, the groups did differ, suggesting that while explicit learning may affect performance on tasks, it does not necessarily affect implicit learning of patterns. It may be that the explicit condition of the task induced a dual-task-like state in the participants, where they treated the black items as one set of stimuli and the gray items as a separate set, and attempted either to attend to the two sets separately or to focus only on the black set and inhibit the gray set. If this were the case, it may have induced excess cognitive load and thus increased RTs, obscuring learning effects. While such an interpretation corresponds nicely with the cognitive control elements of the HBH, it neither contradicts nor enhances any predictions of the ADH.

Song et al.'s (2009) results encourage an interpretation in the style of Reingold and Merikle (1988) when comparing data gathered in implicit and explicit conditions. Most other researchers assume that the acquisition of explicit knowledge precludes the acquisition of implicit knowledge, and thus use a direct-only measurement task for the explicit condition and an indirect-only task for the implicit condition. By crossing an explicit learning condition with both direct and indirect measurements, Song et al. found that the indirect measurement of learning was still more sensitive to sequence acquisition than direct measurement in the explicit learning condition. These results demonstrate that explicit learning does not necessarily "block" implicit learning, at least as operationally defined in terms of performance gains on indirect measures of sequence knowledge. Presumably, this discrepancy between performance on direct and indirect measures could be the source of the age effects observed in the other studies on instructional effects, although without a younger comparison group in the crossed experimental design it is difficult to know whether this is likely.

Combined with the effects of attentional switching tasks, the case for intentional instruction effects as an indicator of degraded cognitive control behaviors during performance rather than the interference of explicit learning processes with implicit learning becomes stronger. If the two issues – cognitive control during performance and learning of sequences – are at least partially dissociable, then dual-task age effects should also lessen once the secondary task is removed, similar to the dissolution of instruction age effects in the uncued segments of Song et al.'s study. Additionally, other tasks that measure executive function/cognitive control, such as the Stroop task, complex figure reproduction, or traditional working memory tasks, should predict performance during the "explicit" portion of a task such as Song et al.'s, but not during the "implicit" portion.

The distinction between cognitive control during performance and true learning of the target relationships mirrors the central conflict between the two AB models: while the HBH argues that the intended relationships are in fact learned, but that knowledge is obscured by interference during retrieval, the ADH asserts that no such learning occurs. This significant overlap in concepts means that evidence for performance effects over learning effects, like Song et al.'s study, is nicely consonant with the HBH, although it is not directly supportive of either AB model. The current studies use only implicit instructions to eliminate the potential for an interference of instructions on task performance as opposed to learning success, relying on the direct/indirect measurement distinction to access explicit and implicit knowledge, respectively.

2.4 **Processing speed**

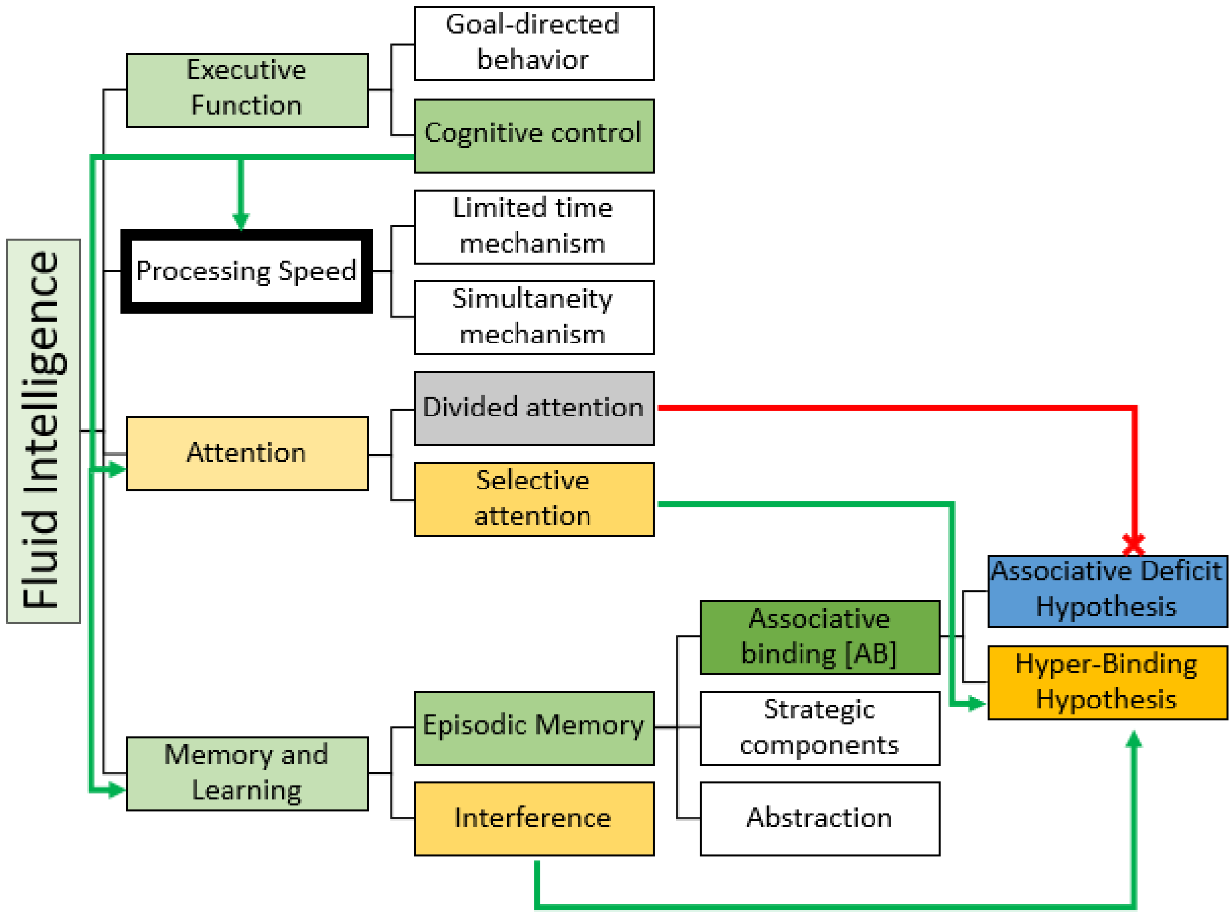

Figure 9: Hierarchy of processing speed concepts, situated within broader cognitive context

The speed of information processing is known to decline with age. Robust age differences in performance are evident in cross-sectional studies involving cognitive tasks like same-different judgments and digit-symbol substitution, as well as perceptual tasks like digit cancelation (Blazer et al., 2015). Longitudinal data (Sliwinski & Buschke, 1999) confirms that these age differences reflect a decline over time of processing speed, and indicates that the rate of change increases as individuals' ages increase.

This relationship is so strong that a proposed theory of cognitive aging suggests that decreased processing speed underlies many of the other differences in cognition between younger and older adults. The Processing-Speed Theory of cognitive aging (Salthouse, 1996) suggests that decreased processing speed limits cognition via two mechanisms: first, the "limited time" mechanism, which posits that when a finite amount of time is available for processing (either because of some task-induced time limit or through concurrent processing demands), earlier operations may take so long that they excessively restrict the available time for later operations. Such a mechanism would contribute to poorer performance on complex tasks intended to test any number of other cognitive systems. Second, the "simultaneity" mechanism, which asserts that when operations take longer, memory demands increase: a longer processing time means that products of earlier operations must be retained longer while later operations are performed. By the time these products are required, they may have decayed beyond usefulness, or they may have become obsolete if the conditions of the task are rapidly changing. This would contribute to apparent declines in performance on tasks involving memory and attention. Empirical support for these claims is provided by statistical analysis of massed cognitive performance data across age groups, which found that measures of processing speed mediated the relationship between age and general cognitive ability, and did so more strongly than measures of vocabulary, memory, or fluid intelligence (Salthouse, 2009a).

Processing speed is theoretically important to implicit learning for several reasons. First, reaction time is a common measure of implicit knowledge and, by extension, implicit learning. If reaction time becomes more variable with age (Salthouse, 2000), then traditional measures of implicit learning may be less sensitive in older individuals than in younger adults – a hypothesis borne out by empirical testing, where RT is sometimes found to be less sensitive than accuracy at detecting age effects (e.g., Bennett et al., 2007). Second, the processing speed theory of cognitive aging suggests that tasks of low complexity may be less affected by differences in processing speed than more complex tasks – a prediction again confirmed by empirical testing: older adults show learning of lower-order sequential structures, but show no learning of higher-order structures when the number of sequential elements is held constant (D. V. Howard et al., 2004). Third, the timing of the task itself may also determine how much processing speed affects performance: as identified by the simultaneity mechanism of the processing speed theory of cognitive aging, a task with rapidly-changing conditions might be more affected by a difference in processing speed than a task with relatively stable conditions would be – a prediction that, like the HBH, is arguably supported by the presence of age effects in the ASRT, where elements of the target structure are presented sequentially, and the absence of age effects in contextual cueing, where all elements of the target regularity are presented at once.

Aging effects in implicit learning have been shown to relate to processing speed. Feeney, Howard, and Howard (2002) used the ASRT to investigate whether age-related declines in IL start in middle age, as declines in speed of processing do (Salthouse, 2009b). Participants were divided into two age groups using a median split. A three-way ANOVA confirmed that there was a significant main effect of age such that older participants were slower to respond but more accurate, and that they showed smaller differences between patterned and random trials on both RT and accuracy measures. Hierarchical regression modeling found that scores on a measure of processing speed (the Digit Symbol Substitution task of the WAIS-III) predicted age-related variance on accuracy data, but that age was required as an additional predictor for the group differences in RT data. These results indicate that the age-related decline in processing speed may be heavily responsible for aging effects on sequence learning tasks, but that other factors may also influence RT measures. It is important to note that some standard measures of processing speed, including substitution tasks, are considered "high-distraction" because many items are presented concurrently and the participant must inhibit all but the current item to perform the task successfully (Lustig et al., 2006). When the test items are presented one at a time, older adults tend to improve their performance on substitution tasks whereas younger adults do not, suggesting that reduced inhibitory control and the resultant increased interference contribute significantly to older adults' performance on this task. Therefore, the observed relationship between the Digit-Symbol Substitution task and measures of IL could reflect the influence of individuals' inhibitory control (supporting the HBH model), their processing speed (supporting the processing speed theory), or both.

To test whether older adults' longer RTs degrade performance through the simultaneity mechanism proposed by Salthouse, Howard et al. (2007) manipulated ASRT interstimulus timing directly and indirectly in younger adults. Direct manipulation of interstimulus timing to replicate older participants' patterns led to more accurate and marginally slower responses, and a smaller learning effect on accuracy, but a larger learning effect on RT – suggesting that while the elongated interstimulus interval degraded accuracy of learning, it facilitated learning as measured by response time, unlike older participants who show disadvantages in both measures.

Howard, et al. (2007) also manipulated interstimulus timing indirectly, through visual degradation of the stimulus. This yielded relatively similar RTs to older adults' performance in a previous study. In this manipulation, the learning effect on accuracy was again decreased in the degraded group compared to the control group, while learning effects on RT were not significantly different between the two groups. In direct comparison with the previously-collected data from aged adults, younger adults from the degraded group showed more accuracy-based learning late in training, but similar effects early in training. Contrastingly, RT-based learning effects were equivalent between the two groups. The possibility of performance, rather than learning, effects was discounted via analysis of a final, non-degraded block, wherein participants showed overall improved RT and accuracy, but no increase in learning-indicative differentials between patterned and random trials.

The ADH might account for these RT manipulation results via conscious strategy use: during interviews following the tasks, participants indicated that they thought a pattern was present, although none could describe the nature of the pattern with any accuracy. It is possible that the suspicion of a regularity within the stimulus led these young adults to employ learning strategies, which did not lead to the successful acquisition of explicit knowledge (directly tested via accuracy; c.f. Reingold & Merikle, 1988) but did facilitate implicit sequence learning (indirectly tested via RT). Since older adults tend not to spontaneously apply learning strategies during associative tasks (Naveh-Benjamin et al., 2007), and older adults' alleged associative deficit does not allow them to benefit from conscious effort during learning as much as younger adults do (Naveh-Benjamin, 2000), such an account could explain the pattern of results seen here.

The HBH, however, has more difficulty explaining these results. One possibility is that the timing manipulation widened the younger adults' "bandwidth of attention." Because selective attention to only the target stimulus did not lead to a speed advantage during the task (given that the interstimulus timing was unconnected to the response time of the participant,) it is possible that the young adults began attending to the items that preceded and followed a given item and building associations in a manner more similar to older adults. This would lead to heightened interference during retrieval and could explain the decreased accuracy; however, the benefit to learning as measured by RT cannot also be accounted for using this explanation.

These results indicate that the simultaneity mechanism can account for much, but not all, of the observed pattern of age-related effects on implicit learning. In particular, the measure most sensitive to aging effects – accuracy – is similarly affected by aging and increased interstimulus timing early in the learning process, but differences emerge later in the process. The processing speed theory of IL age effects can account for this difference by arguing that younger adults may be able to use other cognitive resources unavailable to older adults to compensate for the challenges to the simultaneity mechanism posed by increased interstimulus timing. Loading other resources during this interstimulus time (by introducing a secondary memory or attention task, for instance) could test this assertion.

Forman-Albierti et al. (2014) found evidence inconsistent with the simultaneity account of age effects in IL by testing whether eliminating short-term memory demands by keeping antecedents onscreen ameliorated aging effects on sequence learning. This experiment used a modified triplet-learning task. Like the traditional TLT, each trial consisted of two cueing events and a target event to which the participant responded. Unlike the traditional TLT, the two cueing events remained onscreen (colored red) until the target event (colored green) was presented. In 80% of trials, the location of the first cueing event predicted the location of the target event, while the remaining 20% of trials were randomly generated. As in most studies of implicit learning and aging, older participants performed more accurately overall than younger participants did. Younger adults showed significant RT and accuracy *differences* between patterned and random trials, indicating that they learned the relationship, whereas older adults did not show these learning effects on either measure. These results are somewhat surprising, as older adults have previously shown a learning effect on second-order structures in the unmodified TLT (J. H. Howard Jr. et al., 2008). Thus, the age-related decline in implicit learning was not ameliorated, and may even have been enhanced, by reducing memory demands. Furthermore, participants' performance on the modified TLT was not predicted by traditional measures of working memory (forward- and backward digit span tasks), nor by a measure of processing speed (digit-symbol substitution). The authors argued that this pattern of results suggests against a simultaneity-mechanism-based explanation for aging effects in implicit sequence learning. Instead, Forman-Albierti and colleagues suggest that an age-related decline in associative memory – i.e., the ADH – better explains the data: if older individuals are specifically less likely to form associations between stimuli, then the lack of facilitation from reducing short-term memory demands and the lack of a predictive relationship between other cognitive measures and implicit learning performance are unsurprising. While the authors use the ADH to explain these findings, the findings do not necessarily support the ADH. According to the HBH, the irrelevant second stimulus appearing onscreen with the critical first and third stimuli would have caused older adults to automatically bind these items together, leading to noisy associative bindings and memory interference during retrieval. If younger adults modulated their attention more effectively during the task, emphasizing the third item because it required a response and the first item for primacy reasons, they may not have stored the associations with the second item as strongly and thus experienced less interference in retrieval during later trials.

In sum, the HBH offers compelling explanations for findings linking performance on speed-of-processing measures to IL performance, as well as the lack of facilitation from simultaneous stimulus presentation during the TLT. Meanwhile, the ADH may offer insight into why manipulating interstimulus timing partially replicates aged adults' IL performance in younger adults. More specificity in testing of processing speed as opposed to cognitive and/or memory control are needed if a processing speed theory of age effects in IL beyond the effects of AB is to be supported.

2.5 **Intelligence**

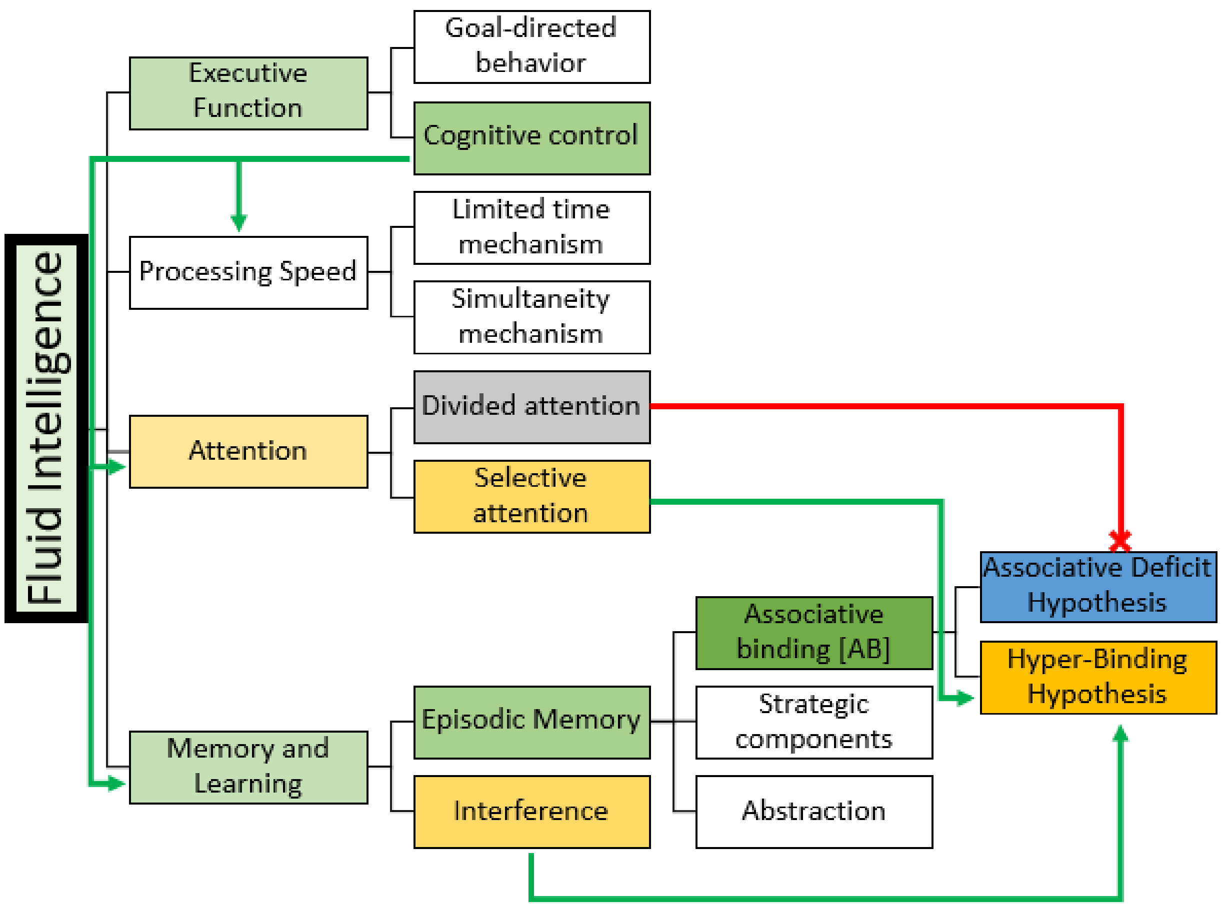

Figure 10: Hierarchical relationship of fluid intelligence to previously-discussed cognitive concepts

All of the previously discussed cognitive capacities, in concert with many other factors, compose the overarching construct known as intelligence. A traditional way to talk about aging effects on intelligence is by dividing intelligence into *fluid* and *crystallized* components (Blazer, Yaffe, &

Liverman, 2015). Crystallized components are those cognitive facets which are relatively static, such as semantic memory. Fluid components are those facets which are necessary for adaptation to ongoing input, such as attention. Crystallized components are usually insensitive to the aging process until late in life, whereas fluid components tend to decline with age (Schaie & Willis, 1996).

This narrative, though widely accepted, is difficult to reconcile with the apparent age-invulnerability of some types of implicit learning. For example, a study of contextual cueing (Merrill, Conners, Roskos, Klinger, & Klinger, 2013) compared college-aged adults with older individuals in terms of general intelligence and implicit learning. Older participants completed the Mini Mental State Examination (MMSE), a rudimentary test of general cognitive function; fourteen participants scored 27 or below, but their data did not alter the study outcome. Younger and older adults also completed the Kaufman brief intelligence test (KBIT-2), a more involved assessment of cognitive function. The older participant group scored lower on this test than the younger group, but this effect was driven by the subset of adults who also scored poorly on the MMSE.

Matrices for the visual search task consisted of four five-element sets of cartoon characters, with the (sixth-element) target character located in one of those sets. Participants were instructed to click on the set of pictures that contained the target; as in most contextual cueing tasks, training consisted of repeated presentations of a small set of matrices, which deterministically indicated the position of the target. After training, participants completed a set of test trials. Half of the displays in the test phase did not contain the deterministic pattern, while half did.

Errors were so rare across groups that accuracy analysis was not performed. RT analysis revealed the expected learning effect in both groups; while older participants tended to respond more slowly overall, the magnitude of the learning effect did not differ between the younger and older adults. This null result was confirmed through analysis of a metric that self-adjusted for individual differences in RT. Within the older participant group, participants were divided into higher- or lower-functioning subgroups based on performance on the MMSE. Comparisons of these two subgroups again revealed a learning effect -- i.e., lower RTs for patterned trials than unpatterned ones -- but no effect of subgroup and no interaction between subgroup and pattern -- in this case, revealing that general cognitive ability did not affect older individuals' ability to detect and learn the cueing pattern. These findings were confirmed by calculating correlations between KBIT-2 scores and the scaled RT metric, which were insignificant and trended in a negative direction (such that higher KBIT-2 scores weakly predicted lower RT facilitation in the contextual cueing task).

On its face, implicit learning ability is a capacity to adapt to new incoming information. Intuitively, it should pattern with fluid intelligence markers, meaning it should decline with higher age and lower overall intelligence scores. These results tell the opposite story – that implicit learning capacity (in this context, with this type of target regularity) is not related to age or intelligence markers. As discussed in the section on testing considerations, however, this may be a misleading interpretation: if decreased attentional regulation (a component of fluid intelligence) is an advantage, as may be the case in contextual cueing tasks, then a decrease in fluid intelligence would result in improved performance on the task. In other words, the face validity of the task as a measure of a fluid ability may not reflect the reality of the task demands.

Salthouse, McGuthry, and Hambrick (1999) investigated the relationship between fluid intelligence markers such as processing speed and spatial reasoning, crystallized intelligence markers such as verbal meaning, and three measures of implicit learning: AGL, SRT, and paired associate learning. They found that the AGL task yielded apparent age-insensitivity in learning effects, but also that the task was relatively unreliable within-subjects, making null results incredibly difficult to interpret and correlations with other measures artificially weak. The paired associate learning task yielded similarly unreliable results. The SRT, however, showed both evidence of group-level age-invariance and acceptable levels of within-subject reliability. In further analysis, the SRT showed significant positive correlations with several measures of fluid intelligence and a marginally insignificant negative correlation with age – suggesting that, when measured using a task with appropriate levels of intra-subject reliability, implicit sequence learning does not follow the counterintuitive age-intelligence pattern modeled by the contextual cueing data. Of course, given the evidence from Lustig et al. (2006), it is difficult to know how many measures of "fluid intelligence" as a whole are confounded by high demands on selective attention, artificially weighting attentional abilities in this analysis.

The disagreement between data from serial reaction and contextual cueing tasks with relation to age and intelligence could be explained in a few ways. First, it may be that the type of implicit learning measured by the contextual cueing task is fundamentally different from the sequential learning measured by the serial reaction task. If this is the case, it would mean that implicit sequential learning patterns congruently with existing models of aging and intelligence, but implicit covariation learning directly conflicts with those models. Such an interpretation has long been accepted by implicit learning researchers, and some evidence suggests that differences between the underlying neural substrates of sequential and spatial context learning may cause this behavioral dissociation (Howard, Howard, Dennis, Yankovich, & Vaidya, 2004).

An alternate interpretation is suggested by the conclusions of Salthouse and colleagues (1999): the intra-subject reliability of the contextual cueing task is unknown. If this task proves as unreliable as the AGL and paired-association learning tasks, then the lack of aging effects and the lack of a strong association with intelligence markers is both unsurprising and uninformative. Such an interpretation would be easily refuted with intra-subject reliability data, but since none is available, it cannot be confirmed or ruled out. If this interpretation proves to be correct, and contextual cueing tasks are unreliable, then the exploration of aging effects with other non-sequential implicit learning tasks should be a high priority, as without a task comparable in reliability to the serial response tasks it is impossible to determine whether this dissociation of implicit learning "types" in relation to aging and intelligence truly exists.

A final potential explanation is provided by the HBH: while contextual cueing tasks favor participants who attend to multiple relationships at once, the SRT task favors individuals who focus on the sequential relationships and inhibit the noise from randomly-sequenced blocks when completing the patterned blocks. Given this difference, older adults' decrease in selective attention uniquely equips them to succeed in storing and retrieving the multiple associations that inform performance on the contextual cueing task, while hindering them from focusing only on the patterned blocks after encountering random blocks on the SRT task. In this way, a reduction in a "fluid" component of intelligence could simultaneously improve performance on a contextual cueing task and decrease performance on an SRT task. Since the advantage on contextual cueing performance provided by reduced selective attention is likely modulated by other markers of "fluid" intelligence, like speed of processing, the combined result might obfuscate the relationship between fluid intelligence and IL on that task type, whereas the markers of fluid intelligence might all influence the SRT in the same direction, leading to a clearer relationship.

Findings from the fluid intelligence literature thus suggest that the relationship between "intelligence," aging, and implicit learning ability is complex and difficult to categorize. For this reason, exploring the relationships between IL and the various sub-domains of intelligence is a critical first step in being able to fully interpret the existing evidence.

2.6 **Summary**

The theories regarding fluid intelligence discussed in the previous section emphasize the interconnectedness of the various cognitive domains. An examination of aging effects on IL through the lens of AB and its competing models demonstrates that age-related AB differences do not exist in a vacuum. They are connected to age-related changes in other cognitive domains, some of which may contribute to the phenomena that AB accounts aim to explain, or provide competing accounts of age-related IL differences. In addition to the direct evidence supporting the ADH and the HBH, each model is consistent with some of this evidence from other domains, and struggles to explain other results. Both the ADH and the HBH can account for performance effects of divided attention and intentional instructions, as well as the lack of facilitation from simultaneous presentation of stimuli in the TLT (possible evidence against processing-speed models). In addition, the ADH (and not the HBH) can explain the effects of direct manipulation of interstimulus intervals, while the HBH (and not the ADH) can account for the link between standard measures of processing speed and IL performance and the lack of correlation between fluid intelligence measures and performance on contextual cueing tasks.

Broadly, the HBH accounts for somewhat more of the existing evidence than the ADH does, but to date the ADH and the HBH have not been directly and definitively compared, despite past efforts to directly test these competing hypotheses. The current studies seek for the first time to test and compare these hypotheses directly, both filling a gap in the current literature and also providing additional insight into the existing literature. The studies examine the central claims of each model: the ADH suggests that pre-existing associations are less affected by age-specific AB dysfunction, so the current studies examine AB among novel words with semantic content (experiments Ia and Ib), novel words without semantic content (experiment IIb), and familiar words with varying levels of semantic relatedness (experiment IIa). Meanwhile, the HBH suggests that older adults are less able than younger adults to inhibit attention to irrelevant stimuli, so the current experiments test attention to incidental contextual information (experiments Ia and Ib) as well as to explicitly irrelevant secondary stimuli (experiments IIa and IIb). Each experiment uses both indirect and direct measures during and after the learning process, to maximally capture the explicit and implicit knowledge being gained and to distinguish between observed effects on performance and effects on learning itself. In this way, the current studies test the competing AB models within the framework provided by the literature as a whole. Since previous studies have never directly tested these two models against one another (although they have been tested separately,) the current experiments fill a significant gap in the understanding of aging and IL. If we are able to identify which model best describes how age affects the central behavior underlying most IL tasks, the building of associations across items, we can begin to make practical recommendations regarding compensatory strategies for older adults to best leverage IL in daily activities.

3.0 Contextual Dependence: Experiments Ia and Ib

The following two experiments test the responses of younger and older neurologically healthy adults to degradation of target memory cues within intact contextual cues during a linguistic task. Since the contextual cues are incidental to the task, the hyper-binding hypothesis (Campbell et al., 2010) predicts that older individuals will be unable to inhibit these cues as successfully as younger individuals, and thus will retain and retrieve the cues more successfully in a later task. If the contextual cues are increased in saliency during training by decreasing the utility of the target cues, younger adults should cease to inhibit the contextual cues and should show performance similar to older adults on the later contextual cue retrieval task. Thus, the hyper-binding hypothesis predicts that older adults will retain and retrieve contextual cues regardless of the utility of the target cues, and that increasing younger adults' attention to context should decrease the age difference in performance on a task that rewards knowledge of the contextual cues.

By contrast, the Associative Deficit Hypothesis (ADH) suggests that older adults are less likely to form and retrieve associative memories between any given elements, and so predicts that older adults will recall contextual cues less successfully than younger adults. The ADH would expect that if younger adults are induced to recall contextual cues more strongly by reducing the utility of the target cues, the differences in performance between young and older individuals would increase, rather than decrease as predicted by the hyper-binding hypothesis. These predictions are tested by Experiments Ia and Ib, respectively.

3.1 **Method**

3.1.1 **Participants**

We recruited 63 younger (age range: 18-25, mean: 20.73, sd: 2.13) and 54 older (age range: 60-77, mean: 67.06, sd: 4.31) adults without language impairment from Pittsburgh and surrounding communities using advertisements in the community as well as the University of Pittsburgh Introduction to Psychology Participant Pool and the Pitt+Me research participant registry. The older group was recruited using a wider age range than the younger group to imitate the characteristics of the older group in Campbell et al's (2010) study, which had an age range of 60-73 with a mean age of 66.63 and a standard deviation of 4.15 years. These characteristics are also roughly comparable with the older groups in Peterson and Naveh-Benjamin's (2016) study on item-context binding, which had age ranges of 65-85 and mean ages of about 73 years and standard deviations of 5-6 years.

All participants were native speakers of English as determined by self-report. All participants completed standardized screenings to exclude those with frank cognitive deficit, consisting of the Mini Mental State Examination (Folstein et al., 1975) using the authors' suggested cutoff score of 24 (c.f. Bleecker, Bolla-Wilson, Kawas, & Agnew, 1988, who suggest age-specific cutoff scores by decade). Participants also completed an audiometric screening for hearing loss at 40 dB at .5, 1, 2, and 4 KHz.

As in any study on aging, it should be noted here that RT is known to be negatively affected by age, and as such tends to have larger inter- and intra-individual variance in older adults; this larger variance may mask true effects in aging studies that rely on RT as a primary dependent variable. By using hierarchical linear modeling, we controlled for the larger inter-individual variance via random intercepts for participants; the larger intra-individual variance is more of a concern, but one that biases these experiments against the potential Type I error of finding spurious age-related effects, and given that both the ADH and HBH hinge on differences in how the age groups respond to stimuli it should not skew the results toward one hypothesis over the other. Additionally, we know that RT effects in IL have been observed in similarly-sized samples of comparable age ranges (e.g., Campbell et al., 2012), and we used accuracy as a complementary measure to RT, which does not carry the same concerns of decreased intra-individual stability.

3.1.2 **Materials**

Target visual stimuli consisted of three pairs of visually-similar objects (e.g. a paper bag and a cardboard box,) each adapted from the Bank of Standardized Stimuli (BOSS; Brodeur, Guérard, & Bouras, 2014) to match color and size as closely as possible across members of a pair. The objects were chosen to be easily distinguishable using high-visual frequency information (fine details, such as texture and small markings,) but similar in low-visual frequency information (broad details such as color, shape, and size.) Members of each object pair will herein be referred to as object "twins."

Each pair of object twins had an associated pair of background images. Each background-image pair consisted of visually-distinct photographs of similar complexity and conceptual content (e.g. a chair and a small table positioned against a blank wall). We designed the background images such that the target objects could be superimposed upon the images to create a 'scene,' with the target object in the foreground situated within one of the two background contexts. Each twin within the pair had a *frequent* and an *infrequent* background context. Each background image within the pair served as the *frequent* context for one twin, and the *infrequent* context for the other (see Figure 11). Finally, the target object in each scene was digitally blurred in a gaussian pattern, to reduce the visibility of the high-frequency visual information (leaving the low-frequency visual information from the object and all of the background image largely intact), creating a *masked* set of scenes in addition to the unaltered *unmasked* set of scenes (see Figure 11).

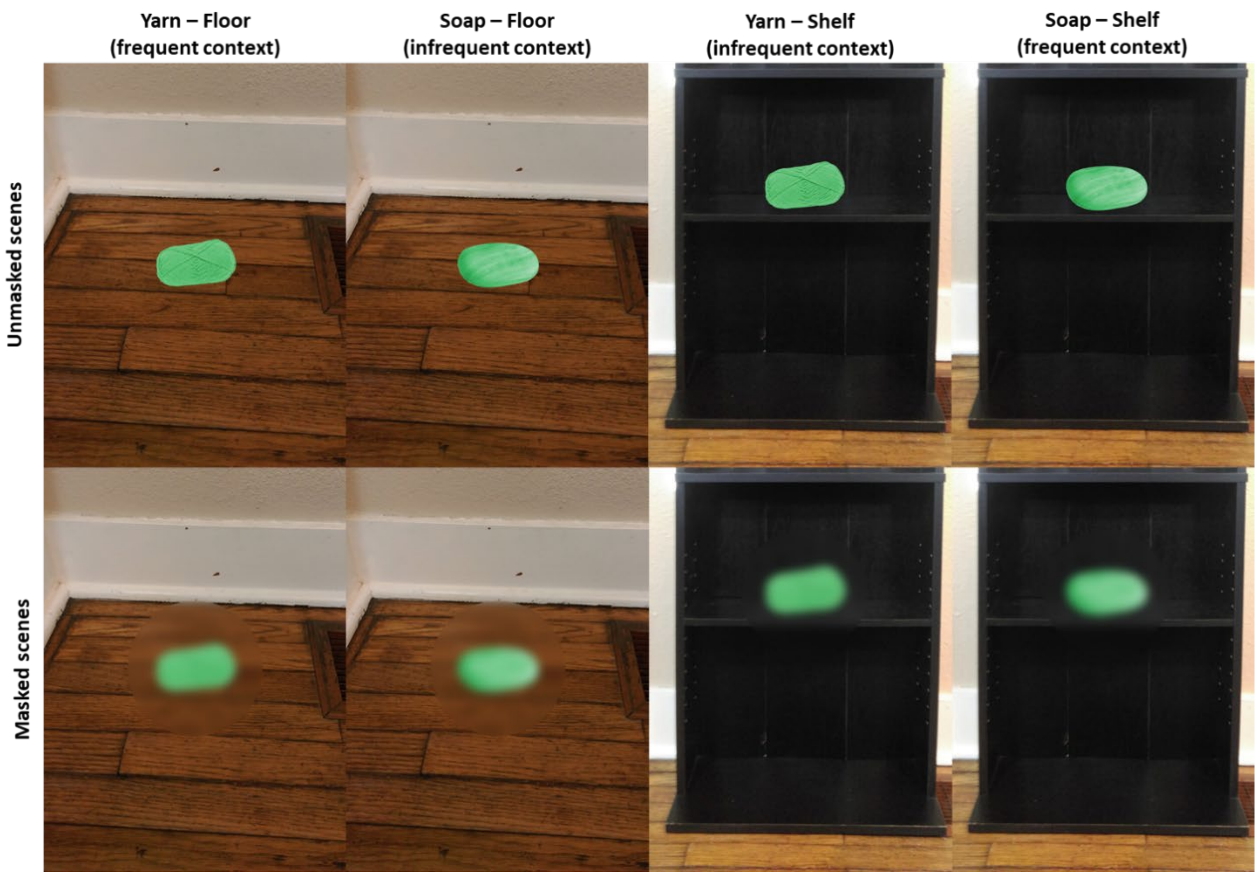

Figure 11: Sample scenes from Experiment I

Fourteen young adults aged 18-25 completed a norming study of these scenes to confirm that the object twins were distinguishable from one another when they were not masked or when the masked versions were presented side-by-side for direct comparison, but that the masked versions were difficult to tell apart when presented in sequence. During this norming study, participants performed two tasks: In the first task, they observed a scene (either masked or unmasked) for 750 ms. Then they viewed three one-second displays filled with letters (to disrupt the short-term perceptual memory of the scene) followed by a second scene for 750 ms. The second scene was either a repetition of the first scene, or a scene with the original object's twin on the same background, with the same masking condition (either masked or unmasked.) After each scene – letters – scene sequence, participants responded to a text screen asking whether or not the two scenes were the same.

The second task of the norming study showed participants two masked scenes simultaneously for one second, then asked whether the two images were the same. As in the first norming task, the scenes were either the same image, or a pair of object twins superimposed on the same background.

T-tests were performed to determine whether participants' ability to distinguish between twins was significantly better for simultaneous presentation and unmasked sequential presentation than it was for masked, sequential presentation. For each of the final object pairs, there was no significant difference between participants' accuracy on direct comparison (M=94.0% accuracy) and their accuracy on unmasked sequential trials (M=91.7% accuracy; $p>0.3$ in each paired comparison,) but that they were significantly more accurate on direct comparison than on masked sequential trials (M=59.5% accuracy; $p<.03$ in each paired comparison.) These results show that the twin objects used in the experiment were distinguishable based on low-frequency visual characteristics (accuracy on unmasked sequential trials,) that it was possible to do so even when these details were reduced through masking (accuracy on masked direct comparison trials,) but that the masking made this distinction more difficult in sequential presentation like that used in the final experiment (accuracy on masked sequential trials.) Each scene had an associated linguistic stimulus. We assigned pseudowords that were originally developed by Misyak, Christiansen, and Tomblin (2010) as novel names to the target objects. These novel names were included in sentences that describe the scenes, e.g. “Someone put the LAELJEEN (box) on the floor.” A native speaker of English recorded these sentences for auditory presentation during the experiment. Participants viewed visual stimuli on a laptop computer monitor, and heard the auditory stimuli via a pair of headphones. Participants were instructed to adjust the intensity of the auditory presentation for their comfort.

3.1.3 **Experiment Ia: Procedure**

Twenty-nine participants from each age group were randomly assigned to complete Experiment 1a. During the training phase, these participants viewed a screen containing one of the *unmasked* experimental scenes above three pseudowords: the novel name for the target image, the name of the other member of the target image pair, and a name from one of the other target image pairs. While participants viewed this screen, they heard a sentence describing the scene. Their task was to click on the pseudoword that they heard during the sentence. Participants completed four training blocks of 120 trials each (twenty trials with each target object.) They encountered each target image twenty times per block; the target image appeared in front of its *frequent* background in 80% of trials, or sixteen times per block, and in front of its *infrequent* background in twenty percent of trials, or four times per block.

Following the training phase, participants completed a two-condition testing phase. Participants encountered each target image in both its *frequent* and *infrequent* context in each condition of the testing phase. In the *unmasked* condition, the testing procedure was identical to the training procedure, except that participants heard a tone in place of the target image’s pseudoword name while listening to the sentence. Participants were instructed to click on the "missing" word. It was expected that participants would respond more quickly, and possibly more accurately, to the items in the *frequent* context than in the *infrequent* context in the unmasked testing condition. Such a pattern would reflect a facilitative effect of familiar contexts on linguistic processing in the presence of meaningful target cues.

In the *masked* testing condition, *masked* scenes were presented instead of the *unmasked* scenes used in the rest of the experiment. It was expected that the addition of visual noise to the target image would reduce the informativity of that image, leading participants to rely more heavily on context; therefore, we expected that participants would tend to react more slowly to the stimuli and/or to erroneously identify a masked target image as its visually-similar partner when it was placed in its *infrequent* context (i.e., when it was placed in its partner's *frequent* context).

Following the testing condition, roughly half of participants were interviewed regarding their subjective experience of the task to determine whether they consciously used the background information during testing.

3.1.4 **Experiment Ib: Procedure**

The remaining participants completed Experiment Ib. The procedure for Experiment Ib was identical to that of Experiment Ia, but the stimuli during the training phase consisted of both the *masked* and the *unmasked* versions of the scenes. Each of the three target object pairs were *masked* in 75% of trials, in both the *frequent* and the *infrequent* contexts; this masking reduced the informativity of the target image during training, which we expected might lead participants to attend to the context more closely than they would otherwise during learning. Participants then completed the two testing conditions exactly as described in Experiment Ia, to allow for direct comparison of the effects of contextual frequency.

3.2 **Experiment Ia and Ib: Analysis and Results**

We analyzed participants' accuracy and reaction times during the testing phase of each experiment (i.e. separately for each training condition) using logistic and linear hierarchical models, respectively. These models included the target object and the participant as random intercepts. Models of RT included both the effects of context frequency and object masking on individual subjects' performance as random slopes. Experiment Ib's accuracy data had the same random slope structure, but the model of accuracy from Experiment Ia included only the effect of image masking as a random slope, as the data could not support both, and model comparisons did not reveal a significant difference in model fit when the context frequency slope was removed ($p=.627$). Fixed effects, all of which were effects-coded, included age group (older vs. younger adults,) context frequency (frequent vs. infrequent background in the test item,) and object masking (blurred or unblurred test item,) resulting in a 2x2x2 design for each model. Models were built in RStudio version 1.0.136, using the lme4_1.1-17 and lmerTest_3.0-1 packages. Including two follow-up models analyzing both experiments together, a total of six models were built; therefore, a Bonferroni correction was applied to the initial α value of .05, adjusting the criterion for significance to $p \leq .008$.

Data were conservatively trimmed to preserve the widest range of responses possible, given the high variance in ages in the older age group. We removed any trials where the participant did not click on one of the words, and any trials where the participant took longer than 10 seconds to respond, as these are both indicators that the participant was not completing the task as intended. This resulted in the removal of 71 out of 2,880 trials, or approximately 2.5% of responses. Response times were included in the analyses regardless of accuracy of response.

We tentatively expected the prototypical main effect of age on IL performance, such that older adults would perform more slowly but more accurately than younger adults overall. Both groups responded with accuracy well above the one-in-three chance rate, as determined by one-sample t-tests (YN: $M = 0.784$, $t = 14.848$, $df = 63$, $p<.001$; ON: $M = 0.670$, $t = 11.07$, $df = 55$, $p<.001$,) indicating that they did successfully learn the relationships between objects and nonwords. According to the mixed-effects models for both the unblurred and blurred training conditions, reaction time on the test block did differ across age groups (Unblurred: $t = 3.959$, $p < .001$, Blurred: $t = 4.726$, $p < .001$,) with older adults responding more slowly than younger adults (Unblurred training: ON M=3162 ms, YN M=2392 ms; Blurred training: ON M=3084 ms, YN M=2061 ms.) This is consistent with the existing literature on aging causing a general increase in reaction times. Accuracy also differed marginally across age groups (Unblurred training: $z = -2.499$, $p=.012$; Blurred training: $z = -2.084$, $p = .037$) with older adults responding less accurately than younger adults. This is unusual among studies of aging and IL, where older adults tend to perform more accurately than younger adults (e.g. D. V. Howard & Howard, 1989, 1992), but it is consistent with either HBH or ADH models of associative binding.

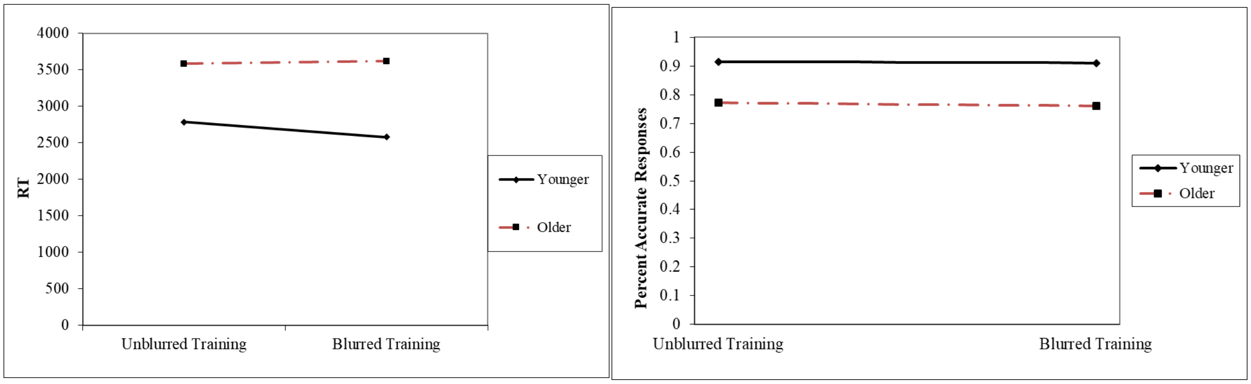

Figure 12: RT and accuracy effects of age group following blurred and unblurred training

We expected that masking would increase the difficulty of the testing phase, leading to a main effect of masking such that participants would be faster and/or more accurate in *unmasked* than in *masked* trials. Consistent with this prediction, participants were less accurate on masked test trials than unmasked trials (Unblurred training: z = -5.504, p < .001, Blurred training: z = -3.006, p = .003.) Masking increased participants' RT following unblurred training (t = 3.824, p<.001,) but not following blurred training (t = 0.495, p=.622), possibly because the blurred scenes were more familiar to participants than the unblurred versions.

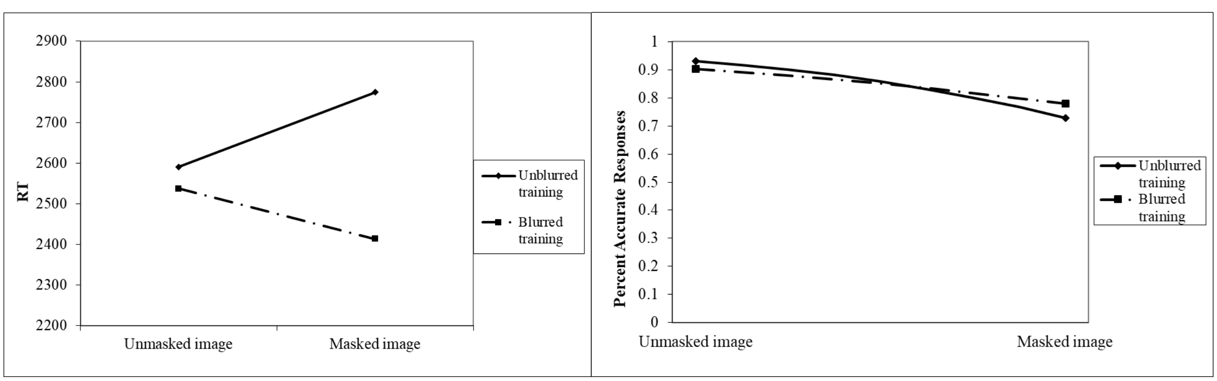

Figure 13: RT and accuracy effects of image masking following blurred and unblurred training

Finally, we expected that context frequency would have a main effect on performance, such that participants would respond more quickly and/or accurately in *frequent* trials than in *infrequent* trials. Participants were less accurate when responding to objects in their infrequent contexts (Unblurred training: z = -3.353, p<.001; Blurred training: z = -3.488, p<.001). Somewhat counterintuitively, participants responded more quickly to objects in their *infrequent* contexts than in their *frequent* contexts, regardless of training (Unblurred training: t = -2.710, p=.007; Blurred training: t = -2.669, p=.008). This unexpected increase in speed when responding to *infrequent* trials could be evidence of a speed-accuracy tradeoff, given that participants responded less accurately overall to infrequent contexts.

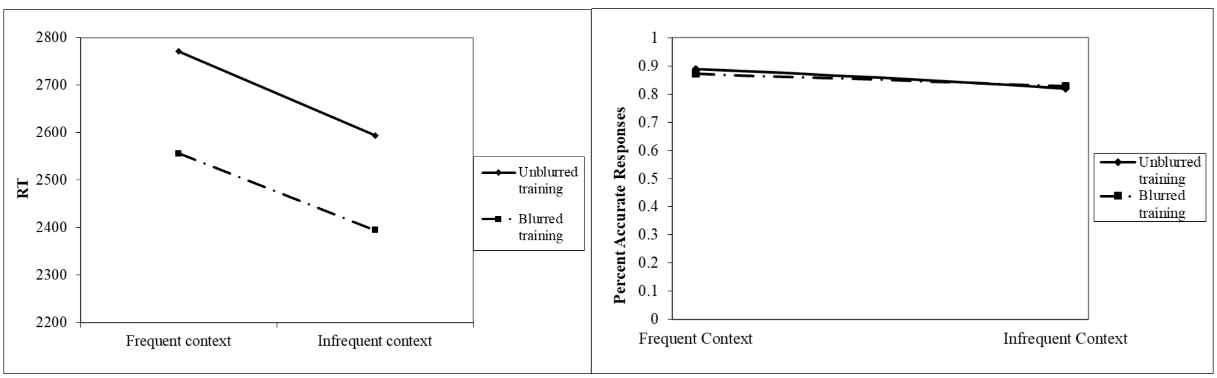

Figure 14: RT effects of context frequency following blurred and unblurred training

These main effects suggest that the task "worked," insofar as it induced age-related effects on IL, and participants' performance appears to have been affected by the primary independent variables of context frequency and object masking. The question of age differences in context frequency were addressed by interaction effects.

First, if cue saliency affects context dependence, then degradation of target cues through masking should have increased individuals' relative reliance on contextual cues during the retrieval task. Therefore, all participants should have shown an increased effect of context on performance in the *masked* testing condition relative to the *unmasked* condition, such that participants responses were facilitated to a greater degree in *frequent* contexts compared to *infrequent* ones when the object was masked; i.e., an interaction between masking and context frequency. Masking and context frequency effects did not interact in the accuracy data (Unblurred training: z = -0.213, p=.517; Blurred: z = 0.102, p=.729), but they did interact on RTs following both the blurred and unblurred training conditions (Unblurred training: t = 3.310, p<.001; Blurred: t = 3.793, p<.001), indicating that masking amplified the effect of context frequency – in low-frequency contexts, participants responded faster if the image was masked than if it was unmasked. This effect could be explained by participants experiencing a confusion effect when the image was unmasked, so that it was clear an object was in an unexpected context. If participants mistook the object for its twin while masked, then such a confusion effect would not be present in the masked condition, meaning they would respond faster.

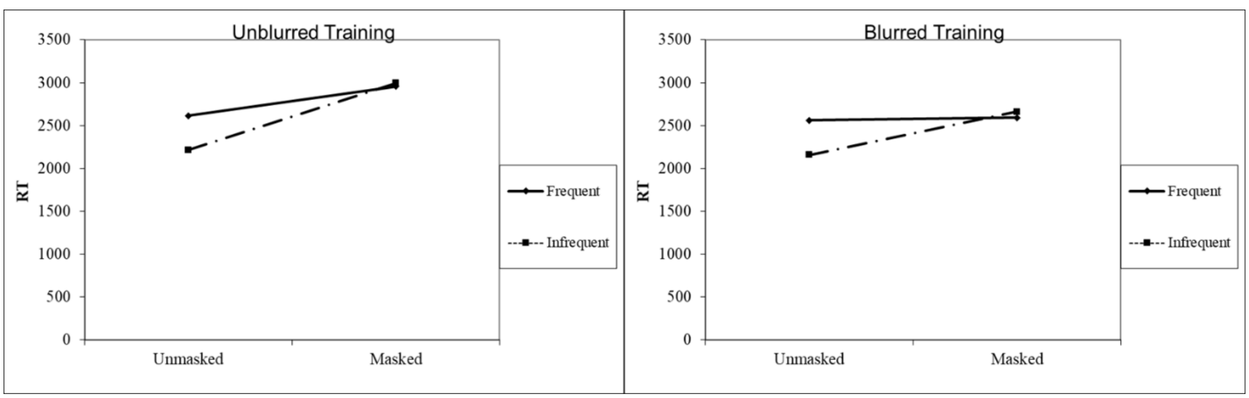

Figure 15: Interaction of image masking and context frequency on RT following blurred and unblurred training

The most critical effect of interest, however, is the three-way interaction between age, context frequency, and masking. The HBH predicts that older adults inhibit irrelevant contextual information less successfully than younger adults during the formation of associative memories, so this hypothesis predicts that the interaction between masking and context frequency on the accuracy and/or speed of their responses should be greater for older adults than for younger adults.

By contrast, a three-way interaction such that this effect is smaller for older adults than for younger adults would contradict the HBH and support an ADH interpretation of implicitly-learned context dependence. Neither accuracy nor RT data showed either of these reaction patterns; in each model, the three-way interaction between age, context frequency, and masking was nonsignificant. The effect size estimates for RT were relatively large (Unblurred training: -459.63ms; Blurred training: 114.45ms) but the variances were high enough to obscure them (266.60ms and 247.90ms, respectively) indicating that future testing with less-varied age groups could possibly provide significant results.

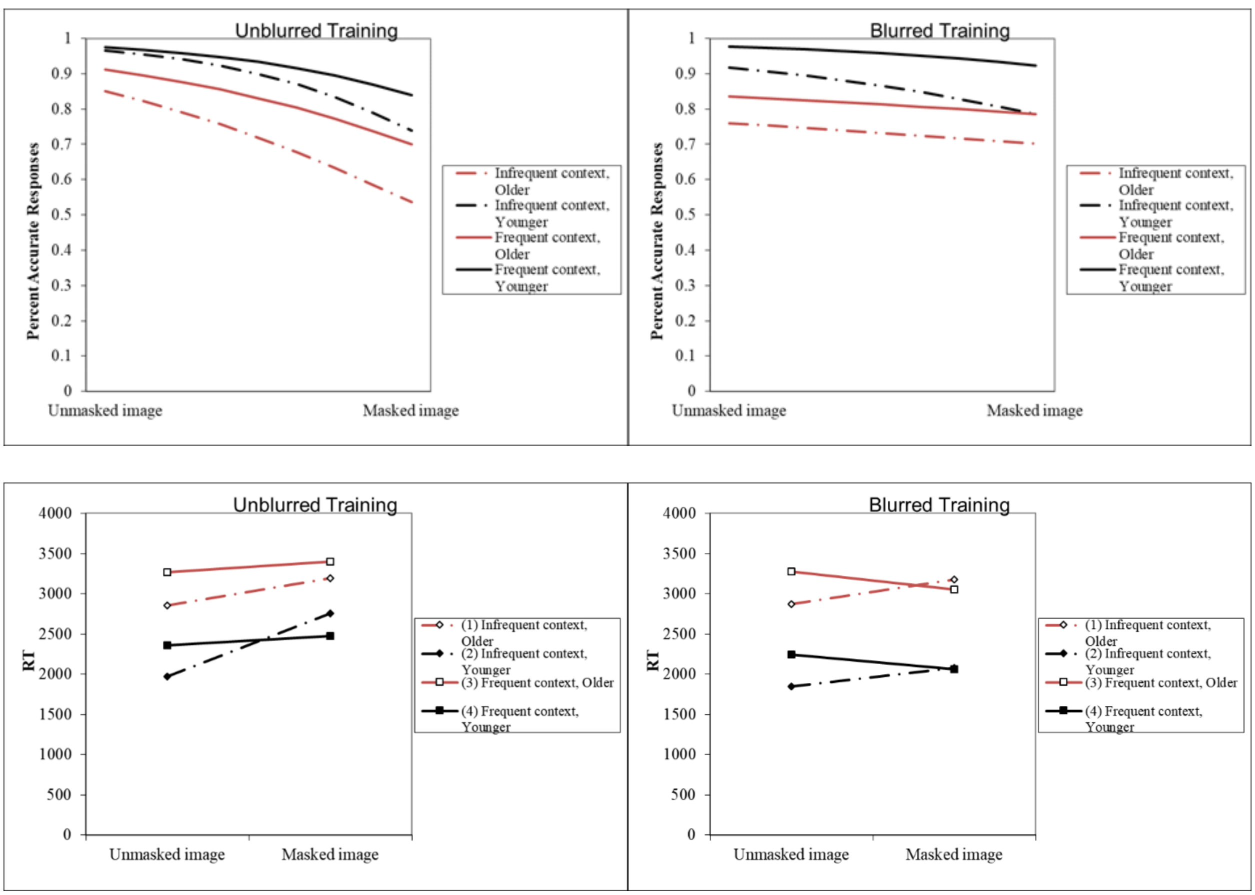

Figure 16: Interaction of age group, image masking, and context frequency on RT and accuracy following blurred and unblurred training

Finally, we conducted an analysis of both experiments together, using 2 (age group) x2 (context frequency) x 2 (testing condition) x 2 (training condition) hierarchical models, with random effects as previously described. We predicted that providing degraded cues during memory acquisition should have induced reliance on contextual cues in younger participants, meaning that younger participants in Experiment Ib should have demonstrated an increased effect of context frequency during testing when compared to younger adults' performance in Experiment Ia. Thus, if the HBH is correct, there should have been a four-way interaction of training condition, age, context frequency, and testing condition, such that the three-way interaction between age, context frequency, and testing condition predicted in Experiment Ia should have been smaller or nonsignificant in Experiment Ib. If the ADH is correct, then the three-way interaction effect should have been larger, as younger adults would have been better at using contextual information but older adults failed to retain and retrieve associative relationships.

The four-way interaction is nonsignificant for both RT ($t = 1.572$, $p=.116$) and accuracy ($z=-.260$, $p=.795$). Again, this is most easily explained as evidence that contextual dependence is unaffected by age. Qualitative analysis of the data does show a decrease in effect estimates for the three-way interaction on RT, however: the three-way interaction is estimated to have an effect of -459.63ms following the unblurred training, and only 114.45ms following the blurred training. As this is both a drastic change in absolute value and a reversal of direction, it may indicate that further research, perhaps with a more tightly-defined age range of older adults, might result in a significant finding. If this interaction were found to be statistically reliable with better-controlled participant groups, it would serve as important evidence that age differences in contextual dependence follow a pattern consistent with the predictions of the HBH.

4.0 Attendance and Interference: Experiments IIa and IIb

In experiments IIa and b, we manipulated the similarity of attended and unattended sets of stimuli to examine the competing effects of scaffolding and interference during associative binding and retrieval within IL tasks. The HBH suggests that older individuals' poorer performance on associative memory tasks is caused by an overabundance of stored associations producing increased interference. If this is true, then manipulating the relative similarity between the attended and unattended patterns should change the amount of interference and thus the magnitude of the age-related disadvantage. In other words, making the unattended stimuli similar to the attended stimuli should decrease participants' ability to recall both attended and unattended stimuli, while making the attended and unattended stimuli dissimilar should increase participants' recall of both stimulus sets.

The ADH, on the other hand, asserts that older individuals' disadvantage in associative learning tasks stems from a specific deficit in storing and retrieving associative relationships. If this is so, older participants should capitalize on similarities *within the attended stimuli* to scaffold the formation of target associations while ignoring the unattended stimuli, meaning that they should not bind unattended items at all or should do so much less successfully than younger adults. The similarity of unattended to attended stimuli should not disproportionately affect the process for older individuals in either case, according to the ADH.

These conflicting predictions are tested in the following two experiments, all of which use a modification of the training and testing procedures described in Campbell et al. (2012) In this original study, participants encountered two parallel streams of stimuli, one which they were instructed to attend and the other which they were told to ignore. The surface task was a 1-back task, where participants monitored the stimuli for repetitions, and pressed a button when they saw a stimulus repeated. After completing this task, participants completed a test of their implicit knowledge of patterns within the stimuli. During the test, the participants monitored a rapidly-presented sequence of stimuli for a particular target item; unknown to the participants, the stimuli during the 1-back task followed particular sequential rules, where each item was part of an invariant triplet set, which were duplicated during the speeded-detection task. Implicit knowledge of the item sequences from the n-back task facilitated the speed and accuracy of performance on the speeded-detection task (see Figure 17 for an overview of the learning and testing paradigms.) Following completion of the experiment, Campbell et al. asked participants whether they considered the n-back and speeded detection tasks to be related in some way, and if so, what the relationship was. None of the participants reported recognizing the sequence of stimuli in the speeded detection task from the sequence in the n-back task, confirming that the sequence learning was learned and used implicitly.

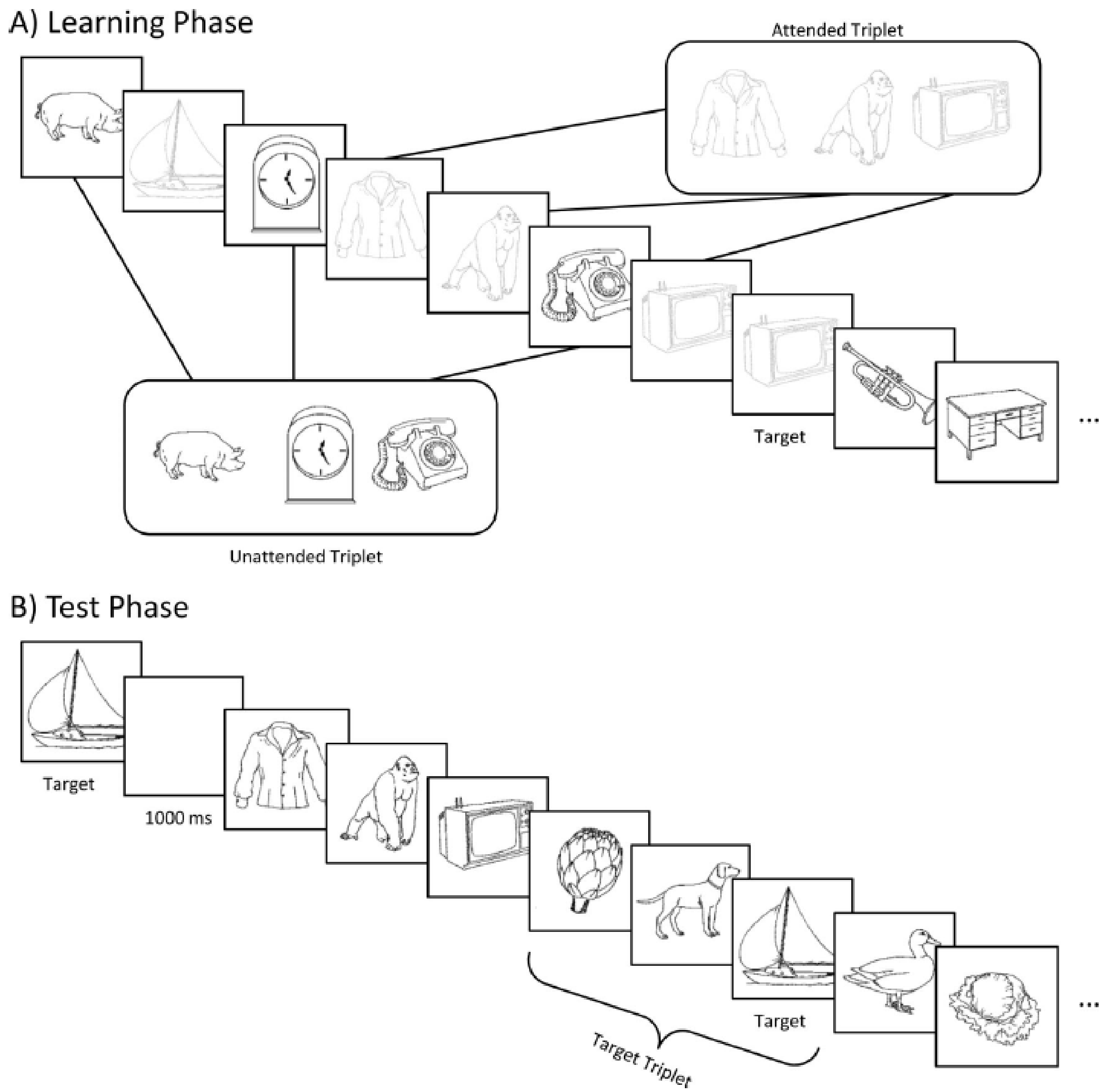

Figure 17: Campbell et al. (2012, p. 651) Learning [A] and testing [B] paradigms. Attended stimuli shown in gray, unattended in black. During learning, participants performed an n-back task on the attended stimuli while ignoring the unattended stimuli. During testing, participants viewed a series of pictures in order from either the attended or unattended stream, and pressed a button when they saw the target picture.

Some major changes were made to these procedures in the experiments described below: first and most critically, given the existing evidence that older adults show outsized effects of stimuli to which they are instructed not to attend (e.g. May, 1999), we manipulated the similarity of the unattended stimulus stream to the attended one. Second, while Campbell et al. used pictorial stimuli, the following experiments used auditory linguistic stimuli. Therefore, instead of the color differences Campbell used to distinguish between the attended and the unattended streams, the following studies used two different voices (from a man and a woman, respectively) to differentiate the stimuli. Speaker information is accessed quickly and automatically by comprehenders (Creel & Bregman, 2011), making this difference ideal for perceptually distinguishing between two sets of spoken linguistic stimuli.

The final major modification to the procedures used by Campbell et al. (2012) in the following experiments was the replacement of the n-back task with a same/different judgement. In an n-back task, the participant is required to indicate trials where they encounter a stimulus that is a repetition of the stimulus presented *n* trials ago. This type of task necessitates either that the participant respond at every trial, or that the participant only respond on trials where they observe the target repetition. If they respond at every trial, participants produce many more "no" responses than "yes" responses, potentially falling into a response set and producing a misleading number of false negatives. If participants only respond on target trials, they may not respond fast enough and appear to have produced a false negative on target trials and a false alarm on trials following the target trials. In both of these cases, it is possible and even tempting for the participant to stop attending to the stimuli and either respond in the same way for every trial or not respond at all. Even if the participant is attending to the stimuli, if the n-back task only requires responses on target trials, participants may not produce the same amount of responses, either by failing to respond on target trials or by responding on non-target trials. Generating a response could affect the way participants process the words, so if the number of responses varies across individuals, it is possible that participants' overall learning experiences may be affected by their willingness or reluctance to respond. By using a same/different judgement task, where participants are required periodically to determine whether a presented written stimulus matches the spoken stimulus they just heard, the following experiments eliminate these problems.

4.1 **Experiment IIa: Hyper-binding & Interference: Semantic Information**

In this experiment, we attempted to replicate in an implicit learning context the facilitative effects of semantic relatedness observed in older adults during explicit associative tasks (Naveh-Benjamin et al., 2003). We included unattended stimuli, to extend previous studies of hyper-binding phenomena to linguistic instead of pictorial stimuli. Finally, we manipulated the similarity between the attended and unattended stimuli to one another, to change the amount of interference participants will experience if they learn both the target and nontarget associations.

4.1.1 **Method.**

4.1.1.1 **Participants.** We recruited thirty younger (aged 19-25, M: 22.4, SD: 1.67) adults from Pittsburgh and surrounding communities using the University of Pittsburgh Introduction to Psychology Participant Pool, extra credit agreements with other courses in the University, and the Pitt+Me registry. Twenty-eight older (aged 61-77, M: 67.53, SD: 3.53) adults were also recruited from the same area via the Pitt+Me registry. Inclusion criteria and screening procedures were the same as in the Context Binding experiments. Many of the participants in Experiments IIa and IIb also completed the activities in Experiment Ia or Ib, although some only completed one or the other due to list counterbalancing needs and other procedural considerations.

4.1.1.2 **Materials.** We developed several sets of four three-word triplets, where the three words of each triplet always appeared in the same order.

As previously described, these stimuli were presented in two streams: one to which the participants were instructed to attend, and the other which participants were instructed to ignore. The triplets were designed to manipulate similarity both *within* the attended stream and *across* the attended and unattended streams, in the following way: each triplet within a set consisted of words that were either *related* or *unrelated* to one another, and each set of four triplets were a *primary* set (i.e., the attended stream), a *foil* set (where each member of a triplet was related to a member of its corresponding primary triplet), or a *distractor* set (where the triplet members were neither related to each other nor to the primary stimuli.) So, an *unrelated-primary* set presented alongside its *foil* set would have no within-triplet similarity, but would have cross-stream similarity; whereas a *related-primary* set presented alongside a *distractor* set would have within-triplet similarity but not cross-stream similarity. Each participant encountered all four possible conditions (*related-primary* x *foil, related-primary* x *distractor, unrelated-primary* x *foil,* and *unrelated-primary* x *distractor.*) To allow for counterbalancing, this design required ten total sets of triplets: two sets each of related and unrelated primary triplets, each having an associated foil set, as well as two distractor sets (see Table 1 for full set of stimuli.)

In this experiment, the first two *primary* sets each contained four triplets of English nouns which were all semantically unrelated (*Unrelated-Primary-A* and *Unrelated-Primary-B*), e.g. PILLOW – FARM – CRAYON. The associated two sets of *foil* triplets were constructed using close semantic neighbors to the nouns in these unrelated primary triplets (*Unrelated-Foil-A* and

Unrelated-Foil-B), e.g. BLANKET – BARN – PENCIL. The second two *primary* sets were constructed from groups of three close semantic neighbors (*Related-Primary-A* and *Related-Primary-B*), e.g. APPLE – BANANA – CHERRY. Two sets of four *foil* triplets were constructed using close semantic neighbors to the words in these related primary triplets (*Related-Foil-A* and *Related-Foil-B*), e.g. ORANGE – STRAWBERRY – PEACH. The final two sets of *distractor* triplets consisted of words that are neither closely related to each other nor to any of the primary triplets (*Distractor-U* and *Distractor-R*), e.g. SUGAR – CROCODILE – MESA. Words were not phonologically or phonetically balanced and ranged from one to three syllables in length.

Given these examples, a participant completing a block with Related triplets and Related streams would encounter the triplet APPLE – BANANA – CHERRY in the Attended stream, and the triplet ORANGE – STRAWBERRY – PEACH in the Unattended stream. A participant completing a block with Related triplets and Unrelated streams would see the same Primary triplet, APPLE – BANANA – CHERRY, but the Distractor triplet SUGAR – CROCODILE – MESA in the Unattended stream.

Table 1: Triplet sets by condition.

	Related Streams						Unrelated Streams		
Related Triplets	**Related-Primary-A**			**Related-Foil-A**					
	1 BED	BLANKET	PAJAMAS	1 MATTRESS	QUILT	NIGHTSHIRT			
	2 APPLE	BANANA	CHERRY	2 ORANGE	STRAWBERRY	PEACH	**Distractor-R**		
	3 RAIN	SNOW	HAIL	3 CLOUDS	FLURRY	SLEET	1 SUGAR	CROCODILE	MESA
	4 FURNACE	FIREPLACE	OVEN	4 BOILER	FLAME	STOVE	2 FREEWAY	ROCKET	WHALE
	Related-Primary-B			**Related-Foil-B**			3 LAWYER	ANKLE	SWITCH
	1 CAR	TRUCK	MOTOR	1 AUTO	SEDAN	TIRE	4 TIDE	MOSQUITO	ASTEROID
	2 SHIRT	JACKET	SWEATER	2 BLOUSE	COAT	SHAWL			
	3 COOKIE	CAKE	ICE CREAM	3 CHOCOLATE	PIE	DESSERT			
	4 BENCH	CHAIR	SOFA	4 STOOL	SEAT	COUCH			
Unrelated Triplets	**Unrelated-Primary-A**			**Unrelated-Foil-A**					
	1 PILLOW	FARM	CRAYON	1 QUILT	CROP	PENCIL			
	2 ROBIN	HAMMER	CURTAIN	2 PIGEON	MALLET	BLINDS	**Distractor-U**		
	3 MOVIE	TULIP	LEOPARD	3 FILM	DAFFODIL	LION	1 STATION	BOTTLE	CEMENT
	4 MOP	SQUID	AIRPLANE	4 BROOM	JELLYFISH	JET	2 VIDEO	PUPPY	SWEATSHIRT
	Unrelated-Primary-B			**Unrelated-Foil-B**			3 SEESAW	VEIN	SALT
	1 KNIFE	TREE	SONG	1 FORK	SHRUB	POEM	4 FATE	POPSICLE	INDIGO
	2 WHISKEY	CLOCK	CANOE	2 VODKA	WRISTWATCH	KAYAK			
	3 SUITCASE	SADNESS	KEYBOARD	3 LUGGAGE	SORROW	TYPEWRITER			
	4 HAMSTER	LIPSTICK	BOOK	4 MOUSE	MAKEUP	NOVEL			

These stimuli were generated using latent semantic analysis (LSA; Landauer, Foltz, & Laham, 1998). The experimenter generated sets of related and unrelated triplets as described above, then checked the semantic distance between members of the triplets using a matrix comparison via the LSA website (Laham, 1998). Relationships that were intended to be similar (i.e. all members of related primary and foil triplets, and foil+primary word pairs for unrelated triplets) were required to have a strength of 0.3 or higher, while relationships intended to be dissimilar (i.e. distractor triplets relative to primary and foil triplets, and members of unrelated primary and foil triplets) were required to have a strength of 0.15 or lower. This rough “sorting” of relationships between the words in stimuli was used as a starting point for checking the semantic relationships between potential stimuli prior to norming using human subjects.

Once the stimuli were generated, they were normed using an online survey of native English speakers aged 18-30, recruited via social media and word-of-mouth. Participants were shown a word from a primary or distractor triplet (e.g. primary word BED) and asked to indicate whether each word in a list was "related in meaning" to the given word. The comparator list contained the remaining members of the word's triplet (e.g. primary words SHEETS, PAJAMAS), all three words from the set's foil triplet (e.g. MATTRESS, QUILT, NIGHTGOWN), and all three words from the remaining primary or distractor triplet (e.g. distractor words ALLIGATOR, BATHTUB, FORK). For each comparator word that a participant marked as "related," the participant then used a slider to indicate how strong he or she considered the relationship to be. Words that the participant did not mark as being "related" were given an automatic strength rating of zero. This two-part process was employed to prevent participants from needing to perform the inherently confusing process of trying to rate the "strength" of a relationship they did not consider to exist between two words. It provided two metrics of word relatedness: relationship *existence* and relationship *strength.*

Participants completed this process for each word in each primary triplet, and for two members of each distractor triplet, allowing word-pair relationships for each possible pairing in a set. Words that were intended to be related – i.e. primary words and their foils – were required to have a strength rating of at least 30/100, and words that were intended to be unrelated – i.e. distractors and members of unrelated primary triplets – were required to have a strength rating of less than 15/100. If a word did not meet these criteria, it was replaced with a different word and the set was re-normed. Four rounds of norming were completed, with a total of sixty-five responses.

With the stimuli finalized, each triplet in a set was arbitrarily assigned a number (1, 2, 3, or 4; see Table 1 where, for example, Triplet 3 in the set Related-Primary-A is “RAIN – SNOW – HAIL.”) As described in Campbell et al., the triplets were arranged into input streams. Each of the four triplets in a given set (for example, Related-Primary-A or Distractor-U) appeared twenty-four times in the stream, for a total of 96 triplets comprising 288 words in a stream. One attended stream and one unattended stream would be combined to form each of the four training “blocks” of the experiment (see Table 2 for examples of triplets from each stream.)

To determine the order of the triplets within each stream, we used the SequenceGeneration2008 computer program (Remillard, 2008), which allows the user to semi-randomly generate a sequence of a specified number of elements with chosen frequencies and allowed contexts. Our four-element sequences (the four triplets that make up a stream) were constrained by length (96 total triplets,) by frequency (each triplet appeared twenty-four times,) and by context (no triplet could be repeated within two spots of itself, so there were no immediate repetitions of triplets or triplet pairs.) Eight such sequences were generated, for each Attended and Unattended stream in each experimental block.

In each Attended stream, one in every four appearances of each triplet required the participant to respond to a verification probe, a yes/no question following the final word (e.g., “Was FORK the last word you were supposed to listen to?”) The location of these verification probes was determined by using SequenceGeneration2008 to choose six random numbers from 1-24 for each triplet, and placing a verification probe after the corresponding appearances of the triplets. So, if the generated six-number sequence were 5-12-8-10-23-17, the verification probes were placed after the fifth, eighth, tenth, twelfth, seventeenth, and twenty-third times the participant saw the triplet. Half of these verification probes required a "yes" response, and the other half required a "no" response, which was semi-randomly determined using the SequenceGeneration2008 software. These probes were intended only to encourage participants to pay attention during training and were not analyzed.

Having generated the two streams – the Unattended stream consisting of 96 distractor or foil triplets (288 items,) and the Attended stream containing 96 primary triplets and 24 response probes (312 items) – the two streams were interleaved by generating two-element sequences of length 25, with a ratio of 13:12. The difference in cumulative items from each of the streams was never allowed to be larger than 6; if the difference grew to this size, the sequence was hand-edited to reduce the difference (so, if by the nineteenth item in the randomized sequence, there had been thirteen attended items and only six unattended items, the next unattended item would be moved earlier in the sequence to reduce the difference between the streams.) Twenty-four of these sequences were combined, and the streams were interleaved according to them.

For example, for the attended stream "ABC(response)-GHI" and the foil stream "456-123," the interleaving sequence might have read "1-1-2-1-2-1-2-2-1-1-2-2-1," making the final interleaved presentation order "A B 4 C 5 (response to C) 6 1 G H 2 3 I." Table 2 shows the possible combinations of attended and unattended streams to be interleaved together.

Table 2: Counterbalanced stimulus sets for presentation to participants

List	Attended Stream	Attended Examples	Unattended Stream	Unattended Examples
1	Unrelated-Primary-A	PILLOW–FARM–CRAYON	Unrelated-Foil-A	BLANKET – BARN – PENCIL
	Unrelated-Primary-B	KNIFE – TREE – SONG	Distractor-U	RABBIT – SHOE – CHAIR
	Related-Primary-A	BED–SHEETS– PAJAMAS	Related-Foil-A	MATTRESS–QUILT– NIGHTGOWN
	Related-Primary-B	APPLE–ORANGE –PEAR	Distractor-R	ALLIGATOR–BATHTUB – FORK
2	Unrelated-Primary-A	PILLOW – FARM – CRAYON	Distractor-U	RABBIT – SHOE – CHAIR
	Unrelated-Primary-B	KNIFE – TREE – SONG	Unrelated-Foil-B	DAGGER – GRASS – POEM
	Related-Primary-A	BED – SHEETS – PAJAMAS	Distractor-R	ALLIGATOR – BATHTUB – FORK
	Related-Primary-B	APPLE – ORANGE – PEAR	Related-Foil-B	BANANA – GRAPEFRUIT – PEACH
3	Unrelated-Primary-A	PILLOW – FARM – CRAYON	Unrelated-Foil-A	BLANKET – BARN – PENCIL
	Unrelated-Primary-B	KNIFE – TREE – SONG	Distractor-U	RABBIT – SHOE – CHAIR
	Related-Primary-A	BED – SHEETS – PAJAMAS	Distractor-R	ALLIGATOR – BATHTUB – FORK
	Related-Primary-B	APPLE – ORANGE – PEAR	Related-Foil-B	BANANA – GRAPEFRUIT – PEACH
4	Unrelated-Primary-A	PILLOW – FARM – CRAYON	Distractor-U	ALLIGATOR – BATHTUB – FORK
	Unrelated-Primary-B	KNIFE – TREE – SONG	Unrelated-Foil-B	DAGGER – GRASS – POEM
	Related-Primary-A	BED – SHEETS – PAJAMAS	Related-Foil-A	MATTRESS – QUILT – NIGHTGOWN
	Related-Primary-B	APPLE – ORANGE – PEAR	Distractor-R	BANANA – GRAPEFRUIT – PEACH

A male and a female native speaker of English each recorded all of the words in the triplet sets, and these single-word recordings were arranged into the input stream orders as determined by this interleaving process. Half of participants heard the attended stream read by the man and the unattended stream read by the woman, and the other half heard the attended stream read by the woman and the unattended stream read by the man.

As described in Campbell et al., after the participant completed each set of interleaved input streams, he or she performed a speeded detection task as a test of implicit sequence knowledge. The stimuli for this task were the words from the training task, but they were read by a third speaker, whose voice was easily distinguishable from the other two voices. The sound files during the testing phase were sped up to 150% using the tempo adjustment feature of the Audacity® sound editing software, to mimic the ‘speeded detection’ aspect of the task in the original study.

Stimuli sequences for the testing phase were seventy-two series of six semi-randomly-arranged triplets from either the primary, foil, or distractor streams from the training task, where the triplet containing a given target word appeared twice, was not immediately repeated, and was neither the first nor the last triplet. The series of triplets were semi-randomly generated using a custom Python code to meet these requirements. Each word from the training phase was a target in the test phase three times, for a total of 72 test trials: 36 trials from the attended stream and 36 from the unattended stream. The trial order for each test block was randomized using SequenceGenerator2008.

4.1.1.3 **Procedure.** During training, participants were instructed to attend to the voice speaking the Attended stream and to ignore the voice speaking the Unattended stream. They listened to the interleaved streams via headphones. When a word in the Attended stream required a response, a screen appeared on the computer that contained either the target word or another word randomly selected from the same triplet. The participant indicated via button press whether or not the word they were seeing was the word that they had just heard; there was no time limit for this response. Once the participant responded, the recordings resumed playing. (See Figure 18 for an illustration of training procedures).

Each participant heard one related primary stream and one unrelated primary stream interleaved with their respective foil streams, and the remaining primary streams interleaved with the unrelated distractor streams (see Table 2 for a full enumeration of the potential stream combinations). These possible combinations were counterbalanced into four "lists," with each participant encountering one full list of stimuli. Stream lists, target voices, and presentation order of the stimulus streams were counterbalanced across participants.

Following each training block, participants performed the speeded detection task as a test of their implicit knowledge of the triplets. Each trial in this task began with a screen instructing the participant to press a button when they heard a given word, followed by the speeded recordings of the words in the trial series. If participants had knowledge of a given triplet sequence, they should have been more accurate or faster when responding to the third word in the triplet (which had been primed by the other two words in the sequence) as compared to the first word in the triplet (which had not been primed at all; see Figure 18 for an illustration of testing procedures.)

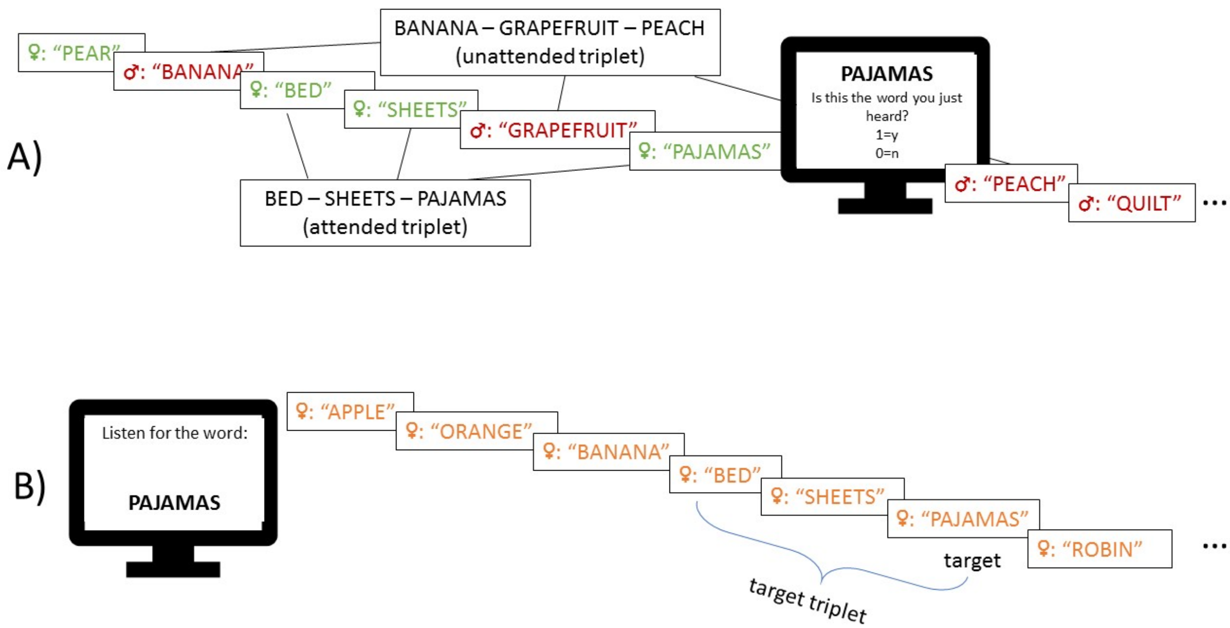

Figure 18: Training (A) and testing (B) procedures. Words in quotation marks are presented via computer speakers or headphones. Colors represent different voices. Ellipses indicate continuing presentation of further stimuli.

4.1.2 Analysis and results.

The main indicator of sequence learning in this experiment is the main effect of triplet position in the speeded detection task. If triplet position (third word vs. first word) positively affected accuracy and/or negatively affected RT, that indicated that the participant had learned the sequence, since participants should be more accurate and quicker to respond to the third word relative to the first if they are using sequence-based knowledge to predict upcoming stimuli. Since this measure of learning success was a main effect, we were interested in how each of the other factors would interact with this effect. Main effects and interactions not including the triplet position factor were of less interest given that they reflected task performance as a whole and not learning performance. The results reported below thus focus on the interactions of interest.

Because anticipatory or delayed responses were likely in this paradigm, the words before and after target words needed to be examined for responses as well as the target words themselves. Responses were centered on the start time of the target word's audio file, so if a participant responded to the word before the target, that response was coded with a negative RT, whereas responses to the target and following word were coded with positive RTs. Any response during this three-word period was coded as accurate.

Hierarchical models of participants' accuracy and RT differences were constructed for the Attended and the Unattended streams respectively. These models used a 2 (first vs. third word x 2 (age group) x 2 (Triplet relatedness) x 2 (Stream relatedness) factor design with the target word and participant as random intercepts and the effects of triplet position and triplet relatedness on individual participants' performance as random slopes. All factors were effects-coded, with first-word, unrelated-stream, unrelated-triplet, and younger-age coded as -0.5 and third-word, related-stream, related-triplet, and older-age coded as 0.5. In combination with the later-described models testing the effects of stream attendance, a total of six models were built; therefore, a Bonferroni correction was applied to the initial α value of .05, adjusting the criterion for significance to $p \leq .008$.

Triplet position (hereafter referred to as the "learning effect") negatively affected RT in both streams (Attended: $t=-13.032$, $p<.001$; Unattended: $t=-11.648$, $p<.001$) and positively affected accuracy (Attended: $z=5.070$, $p<.001$; Unattended: $z=3.66$, $p<.001$). These effects indicate that participants learned the relationships in both the attended and the unattended streams, because they were faster and more accurate when responding to the third word than the first word.

The learning effect interacted negatively with triplet relatedness on participants' RT (Attended stream: t=-4.881, p<.001; Unattended stream: t=-4.648, p<.001), meaning that participants had a stronger learning effect on RT when the triplets were related, probably due to similarity-based scaffolding. Triplet relatedness also interacted positively with learning on accuracy in the Attended stream (z=4.09, p<.001), similarly indicating a stronger learning effect for related triplets; in the Unattended stream, however, the interaction was negative (z= -3.983, p<.001), indicating a stronger learning effect for unrelated triplets. Consistent with this finding, the three-way interaction between the learning effect, stream attendance, and triplet relatedness was significant in the combined model of accuracy (z = -6.352, p<.001) but not in the combined model of RT (t = -.890, p=.373).

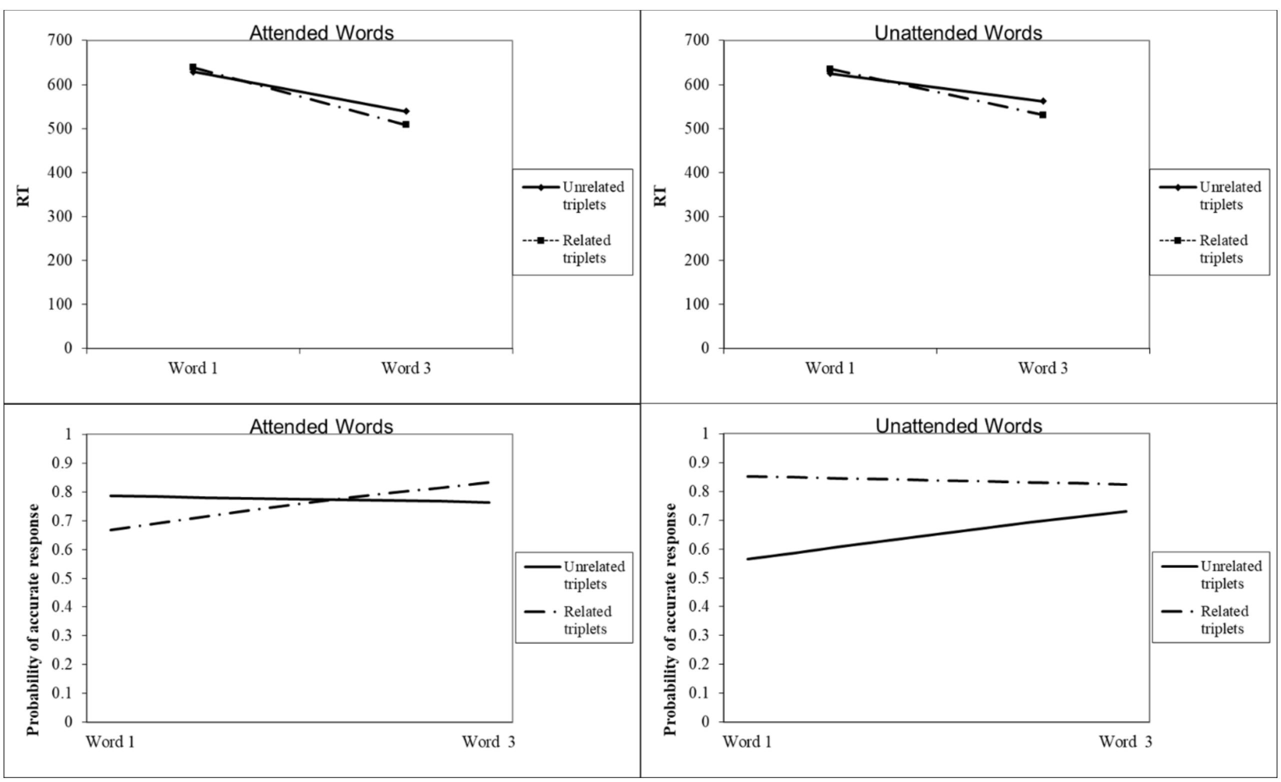

Figure 19: Interactions of triplet relatedness and learning effect on RT and accuracy in attended and unattended streams

Stream relatedness did not interact with triplet position on RT in either stream, nor did this interaction occur for accuracy in the Attended stream. Stream relatedness did, however, interact with triplet position on accuracy in the Unattended stream (z=-2.916, p=.004), indicating that the learning effect was weaker when the streams were related – likely an effect of interference.

Both the ADH and the HBH predict that older adults should have demonstrated less learning of target relationships than younger adults, i.e. that in the Attended streams there should be a negative interaction between age and learning effect on accuracy and a positive interaction between age and learning effect on RT, indicating that younger adults had a stronger learning effect than younger adults. This effect approached significance (i.e. it was significant before correction for multiple comparisons) in the RT data (t=2.430, p=.018), and was not significant in the accuracy data (t=-1.928, p=.054). It is also worth noting that these factors did not interact in either the RT or accuracy data on words from the Unattended stream, which supports an ADH interpretation: if the HBH were true, the reverse interaction might have been expected, with older adults showing a stronger learning effect than younger adults on the Unattended words.

According to the ADH, the existence of previously-formed associations should scaffold older adults' associative memory in streams with related triplets (Naveh-Benjamin et al., 2003) – i.e., there should be an interaction between age, triplet relatedness, and learning effect such that age differences in learning are reduced in the *Related* condition as opposed to the *Unrelated* condition. The HBH does not make specific predictions about the effects of triplet relatedness on associative binding, but it is possible that pre-existing relationships between words within a triplet might help older participants focus their attention on the intended relationships and inhibit any nontarget associations, while younger participants should successfully inhibit nontarget associations in both *Related* and *Unrelated* conditions; this would exaggerate the observed positive effect of triplet relatedness on learning effect in RT as described above. It is also possible that the increased interference from the semantic relatedness of the words might affect older adults disproportionally, consistent with the HBH's assertion that older adults are more prone to interference and distraction by irrelevant information. The interaction between triplet relatedness and learning effect on accuracy data in the Unattended stream does suggest an interference effect of triplet relatedness, which would support this extension of the HBH, and we would expect that effect to be stronger in older adults than in younger adults. Therefore, both hypotheses could account for an age-triplet relatedness-learning interaction where learning is more similar across age groups on Related triplets than on Unrelated triplets, but only the HBH could account for the reverse (i.e. more age group similarity in learning on Unrelated triplets than Related triplets.)

The three-way interaction of Age, Triplet Relatedness, and Learning Effect was not present on RTs for words from either stream, but it was observed in accuracy data from both streams. In the model of the Attended stream ($z=-2.863$, $p=.004$), younger participants showed a very strong learning effect for Related triplets and a small learning effect for Unrelated triplets. Older adults showed a weaker learning effect than youngers on Related triplets and a similar learning effect to youngers on Unrelated triplets. This is the opposite of what we might expect based on the ADH; it would have predicted the opposite interaction, with a larger difference in learning effect in the Unrelated triplet condition than in the Related condition. It is consistent with an interference-based explanation, which could be extrapolated from the HBH as described above.

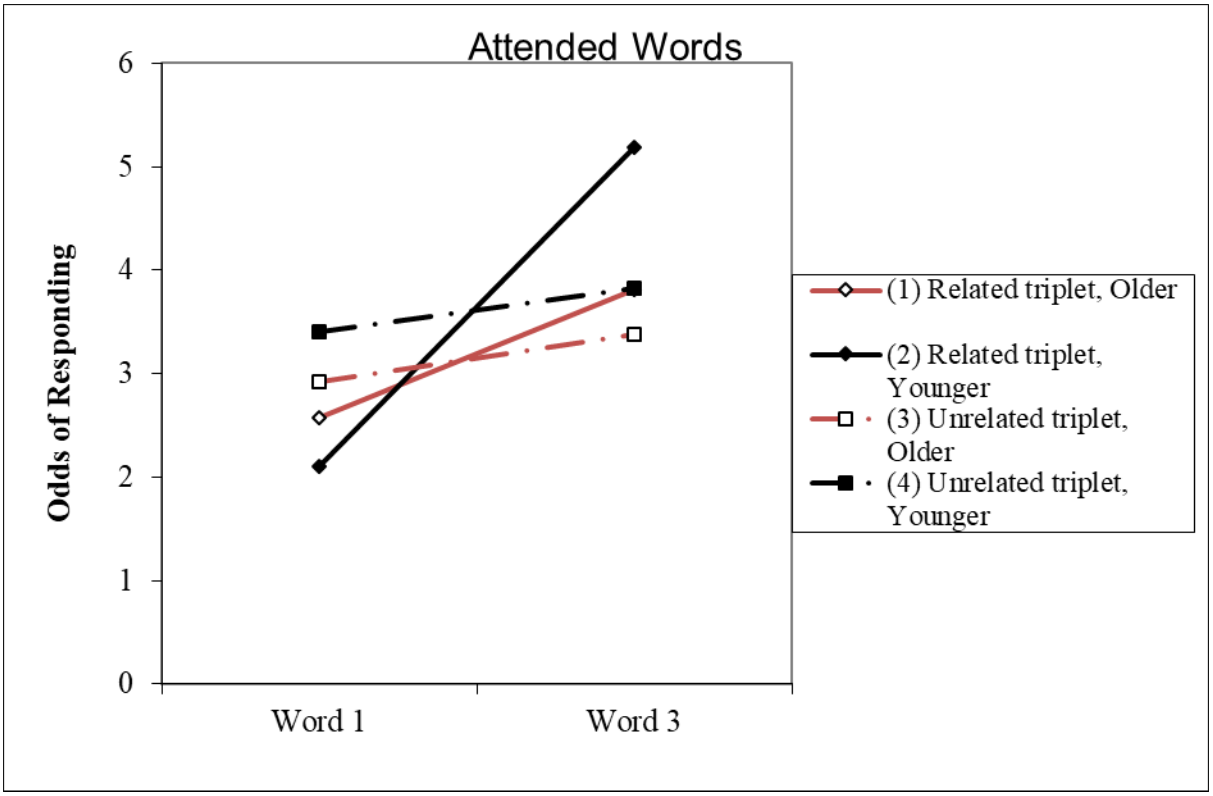

Figure 20: Interactions of triplet relatedness, age, and learning effect on accuracy in attended stream

In the model of the Unattended stream (z=3.167, p=.002), younger participants showed a very strong learning effect on Unrelated triplets and a reverse learning effect for Related triplets (meaning that they were less accurate on the third word than the first,) and older participants showed weak learning effects in both the Unrelated and Related conditions. In other words, in the unattended stream, both age groups learned better when the triplets were unrelated, and this effect was stronger for younger adults than for older adults. If this is a result of heightened interference in the Related Triplet condition, then it contradicts the HBH, which would predict older adults to show more evidence of interference (and thus a larger effect of Triplet Relatedness than younger adults.) It is also counter to the ADH, which predicts that older adults' learning should be scaffolded by triplet relatedness, while this result shows the opposite effect.

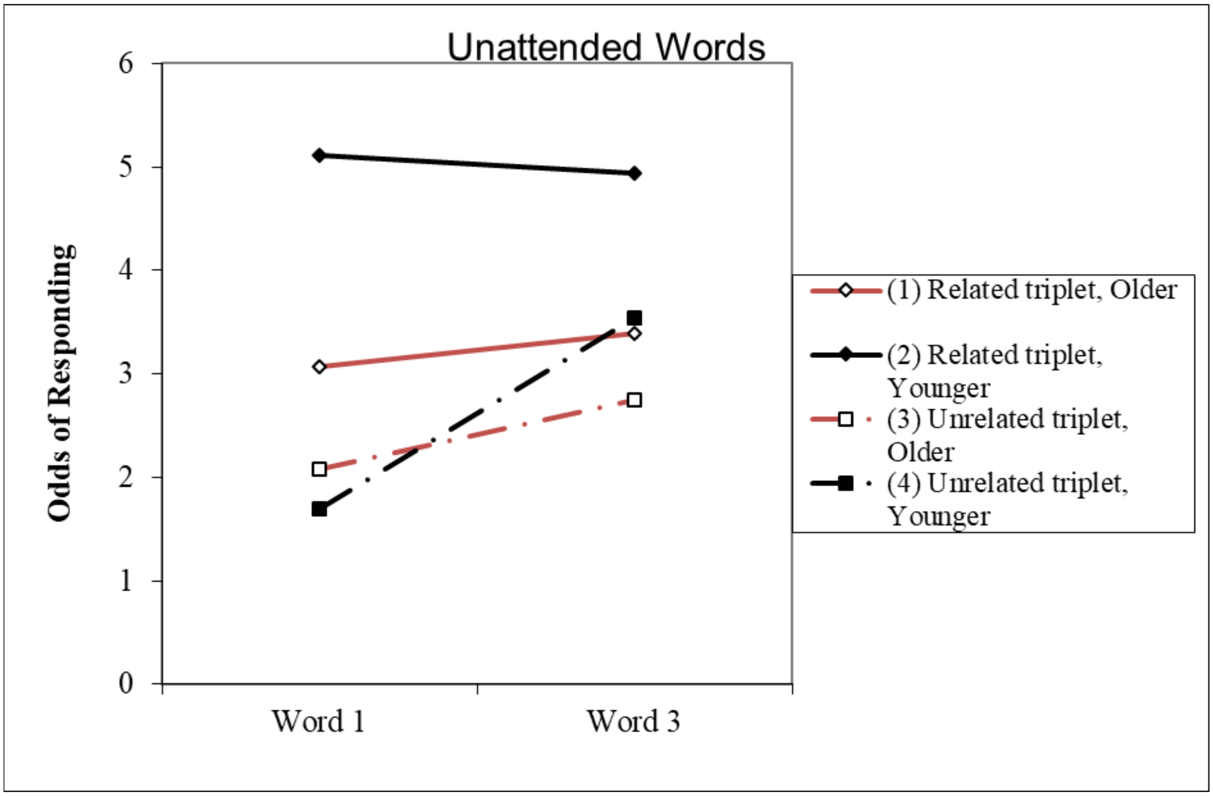

Figure 21: Interaction effects of triplet relatedness, age, and learning effect on accuracy in unattended stream

The HBH predicts that when the nontarget stream is related to the target stream, it should create more memory interference, leading to a negative effect of stream relatedness in older adults, whereas younger adults will successfully inhibit the nontarget stream and be unaffected – i.e., there will be an interaction between age, stream relatedness, and learning effect. The ADH makes no such prediction. This interaction approached significance in the RT data for the Attended stream (t=1.977, p=.048), such that there was a slightly larger learning effect for older adults when the streams were unrelated than when they were related, whereas the younger adults showed little to no difference in learning effect across stream relatedness conditions. No such interaction was present in the RT data for unattended words (t=.589, p=.556) or in the accuracy data for either stream (Attended: z=.119, p=.905; Unattended: z=.991, p=.322).

The HBH predicts a three-way interaction between stream attendance, age group, and learning effect, such that older adults will demonstrate more implicit knowledge of unattended triplets than younger adults, but that younger adults will demonstrate more implicit knowledge of attended triplets than older adults. This effect was found in Campbell et al.'s previous study, absent the current experiment's semantic interference manipulation, and was attributed to younger adults' more successful inhibition of the unattended stimuli. The ADH does not account for this effect and makes no such prediction. This three-way interaction was neither significant in the RT data ($t=-1.652$, $p=.099$) nor in the accuracy data ($z=.972$, $p=.331$).

If stream relatedness modulates interference, as the HBH would predict, then we would expect a four-way interaction between age, stream attendance, stream relatedness, and the learning effect. In this interaction, the age difference on attended streams would be largest in the *Foil* condition and smallest in the *Distractor* condition (as older adults will be less successful at retaining and retrieving the attended stimuli when there is more interference, as in the Distractor condition, but younger adults should be successful in both conditions). The age difference on unattended triplets would be smallest in the *Foil* condition and largest in the *Distractor* condition (as older adults will be less successful at retaining and retrieving the distractor stimuli when there is more interference, but younger adults should be unsuccessful in both conditions). The ADH does not predict this interaction. This interaction is not present in either the RT ($t=-.923$, $p=.356$) or accuracy ($z=.588$, $p=.556$) data, contraindicating this prediction of the HBH.

Finally, if triplet relatedness scaffolds older adults' attentional regulation as suggested by our interpretation of the HBH, then a four-way interaction between age, stream attendance, triplet relatedness, and learning effect would be expected. In this interaction, when the triplets are related older adults should show less of a disadvantage compared to younger adults in the attended stream, and less of an advantage compared to younger adults in the unattended stream. Meanwhile, when the triplets are unrelated, older adults should perform worse relative to younger adults in the attended stream. The ADH predicts no such interaction.

This four-way interaction was not found in the RT data (t=-.514, p=.607), but it was present in the accuracy data (z=4.328, p<.001). When triplets were related, the learning effect for attended words was much larger for younger adults than for older adults, but this age difference was smaller for unattended words. This pattern is counter to the ADH's prediction that older adults should be more affected by semantic relatedness than younger adults. When triplets were unrelated, the learning effect for unattended words was larger for younger adults than for older adults but the learning effects for attended words were similar. In other words: younger adults learned attended words better than older adults when the triplets were related, and they learned unattended words better than older adults when the triplets were unrelated. This is roughly the opposite of what is expected based on the HBH.

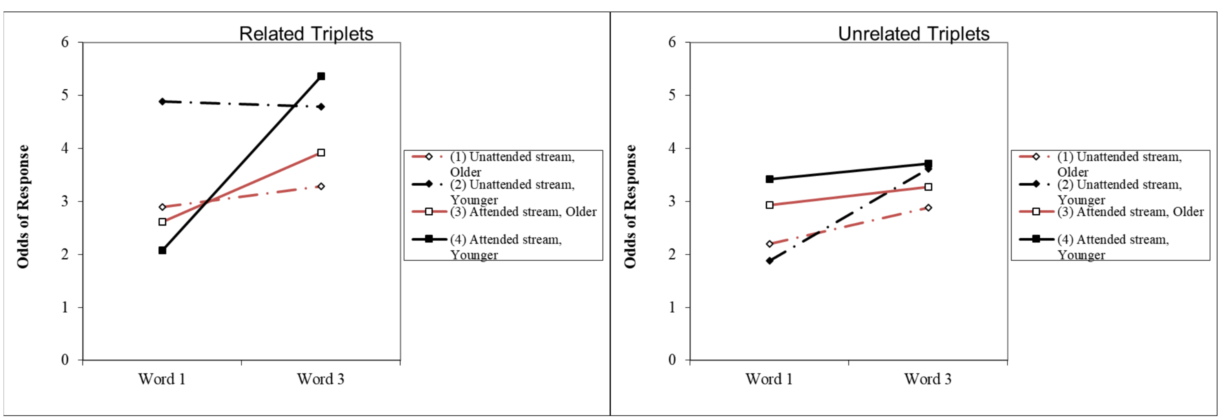

Figure 22. : Effects of stream attendance, age group, and learning on odds of response in related and unrelated triplets

4.2 **Experiment IIb: Hyper-Binding & Interference: Phonological Information**

The second experiment in this series examined whether phonological relationships scaffold associative binding in aged individuals, as semantic relationships have been observed to do (Naveh-Benjamin et al., 2003). The ADH asserts that older adults are better at learning associations between semantically related words because these words have a pre-existing relationship which can be strengthened. If this is the case, then novel pseudowords with phonological similarities should not display the same scaffolding effect, as they cannot have been stored in memory previously and thus cannot have a pre-existing relationship to one another. Even if participants made use of stored sublexical units that do have pre-existing relationships, the additional associative binding that would be required to construct the pseudowords would put older adults at a significant disadvantage in this task as compared to Experiment Ia in the ADH model. In contrast, the HBH can account for the semantic scaffolding effect as a consequence of aided attentional regulation, not a pre-existing relationship, so this hypothesis predicts that phonological relationships may scaffold associative binding between novel pseudowords in older adults in the same way semantic relationships do. Other than the ADH's prediction that triplet relatedness should be less important, the respective hypotheses' predictions are largely the same for Experiment IIb as in IIa: the HBH predicts a three-way interaction of age, triplet attendance, and the learning effect, and one of age, stream relatedness, and the learning effect. The HBH further predicts a four-way interaction of age, triplet relatedness, stream relatedness, and the learning effect, and one of age, stream attendance, stream relatedness, and the learning effect. The ADH predicts none of these interactions, expecting only an interaction between age and learning effect.

4.2.1 **Method.**

4.2.1.1 **Participants.**

Participants were recruited using the same resources and criteria as in Experiment IIa. We enrolled twenty-eight participants in the younger age group (M: 21.07 years old, SD: 2.4 years,) and twenty-seven participants in the older age group (M: 66.59 years old, SD 4.95 years.)

4.2.1.2 **Materials and procedure.**

We again generated primary lists of related and unrelated triplets along with respective foil and distractor lists. Instead of English words, these lists consisted of English pseudowords, generated using the program Wuggy (Keuleers & Brysbaert, 2010) with a default setting of 66.7% overlap of sub-syllabic segments and selecting for English nonwords. The Wuggy program uses a user-specified reference word to generate real or pseudo-words based on syllabic and subsyllabic structure. We generated each pseudoword in a *Related* triplet and its foils using a single reference word (e.g., *burner* generates primary triplet BERJER-FERSER-JERBER and foil triplet BERFER-VERLER-FERJER), and each pseudoword in an *Unrelated* triplet using a unique reference word (e.g. *clover-candle-nation* generates primary triplet PLOBER – LINDLE – NAYBUN and foil triplet FLODER-LANTLE-GAESION). Distractor triplets were generated using the same method as Unrelated primary triplets.

The final recordings of each word were transcribed into the International Phonetic Alphabet by an experienced listener. Words within a set that were intended to be similar had a mean phonological edit distance of 11.4 features and words that were intended to be different had a mean phonological edit distance of 24.9 features, as determined by the string comparison feature of Phonological CorpusTools software program (*Phonological CorpusTools*, 2016) using a feature list derived from the Sound Pattern of English framework (Chomsky & Halle, 1968).

As in Experiment I, there were two sets of four Related-Primary triplets and their respective Foil triplets, two sets of four Unrelated-Primary triplets and their respective Foils, and a final two sets of four Unrelated-Distractor triplets. We arranged these sets into streams and interleaved them as described in Experiment IIa.

The stimuli were recorded and presented as they were in Experiment IIa, and the procedure for the training and testing phases was identical to the previous experiment.

4.2.2 **Analysis and results.**

Data were prepared for analysis using the procedure described in Experiment IIa, including response data from the words surrounding the target word to account for anticipatory and delayed responses. Also as in the previous experiment, we first modeled participants' RT and accuracy during the testing phase using a 2 (Triplet position/ "learning effect") x 2 (age) x 2 (triplet relatedness) x 2 (stream relatedness) factor design, with the target word and participant as random intercepts and the effects of triplet position and triplet relatedness on individual participants' performance as random slopes. All factors were effects-coded and *p*- values adjusted as described in Experiment IIa.

Unlike Experiment IIa, the ADH does not predict an interaction between learning and triplet relatedness in this experiment, as the stimuli are novel pseudowords and thus cannot have a previously-stored relationship with which older adults can scaffold their performance. Therefore, the only effects predicted by the ADH in this experiment are the age x learning effect and stream attendance x learning effect interactions.

The predictions of the HBH do not change because of the use of pseudowords instead of words and phonological instead of semantic neighbors: as the HBH attributes older adults' different associative learning behaviors to difficulty with inhibition, the specific characteristics of the stimuli should not affect the overall patterns of performance. Therefore, the HBH again predicts interactions between the learning effect and age, triplet relatedness, stream relatedness, and potentially stream attendance, as well as three-way interactions between learning, age, and stream attendance; learning, age, and stream relatedness; and possibly learning, age, and triplet relatedness, and finally four-way interactions of learning effect, age, stream attendance, and stream relatedness, and of learning effect, age, triplet relatedness, and stream attendance.

The learning effect, where the third word of the triplet should elicit faster and more accurate responses than the first word, was present in RT data for both attended ($t=-7.439$, $p<.001$) and unattended ($t=-6.317$, $p<.001$) words. The effect was not, however, present in the accuracy data for either stream (Attended: $z=.317$, $p=.751$; Unattended: $z=-1.335$, $p=.182$). These results suggest that, although participants were not more likely to successfully identify the third word in a triplet as compared to the first, they were faster to respond when they did so. This is a departure from the findings in Experiment IIa, where the learning effect was found in both measures.

Triplet relatedness negatively interacted with the learning effect on RT for attended words ($t=-8.097$, $p<.001$), meaning that the learning effect on RT was stronger for words in related triplets than for unrelated triplets. This effect was not present for unattended words ($t=1.065$, $p=.288$), nor was the interaction present in accuracy data for either stream (Attended: $z=1.821$, $p=.069$; Unattended: $z=.945$, $p=.345$), unlike in Experiment IIa where triplet relatedness affected both measures in both streams.

Stream relatedness did not interact with the learning effect in terms of accuracy or RT to attended words (Accuracy: $z=-.216$, $p=.829$; RT: $t=-1.251$, $p=.211$), but the interaction was present for RT to unattended words (RT: $t=-3.987$, $p<.001$), such that the learning effect was stronger when the streams were related. This is a reversal of the findings in Experiment IIa, wherein participants responded more accurately to unattended words when the streams were unrelated, and it is inconsistent with the predictions of the HBH. This finding seems to indicate that similarity-based interference is more of a disadvantage for semantic similarities than for phonological similarities.

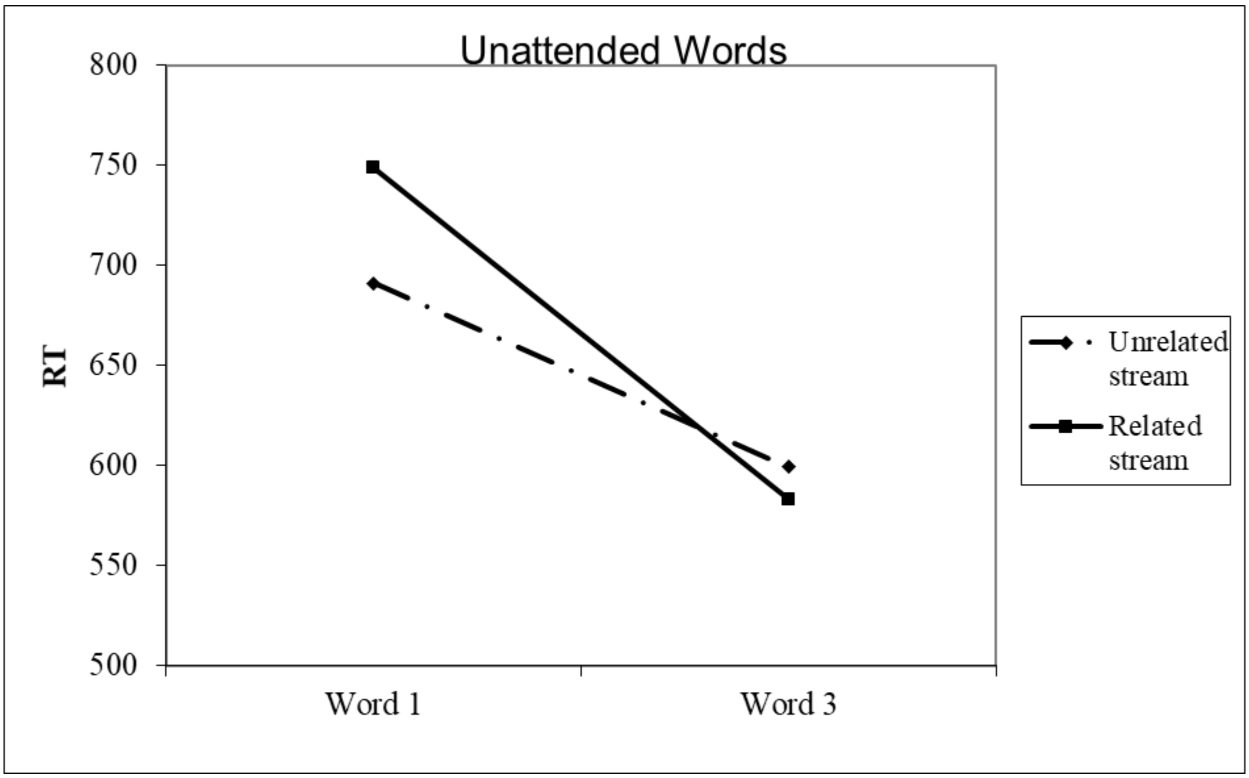

Figure 23: Interaction of stream relatedness with learning effect on RT in unattended stream

The interaction approached significance in the accuracy data for unattended words (z = 1.997, p=.049), but its direction was a reversal of the effect in RT: like in Experiment IIa, participants showed a stronger learning effect when the streams were unrelated. Given its statistical unreliability, this result is difficult to interpret in relation to the above inverse RT effect.

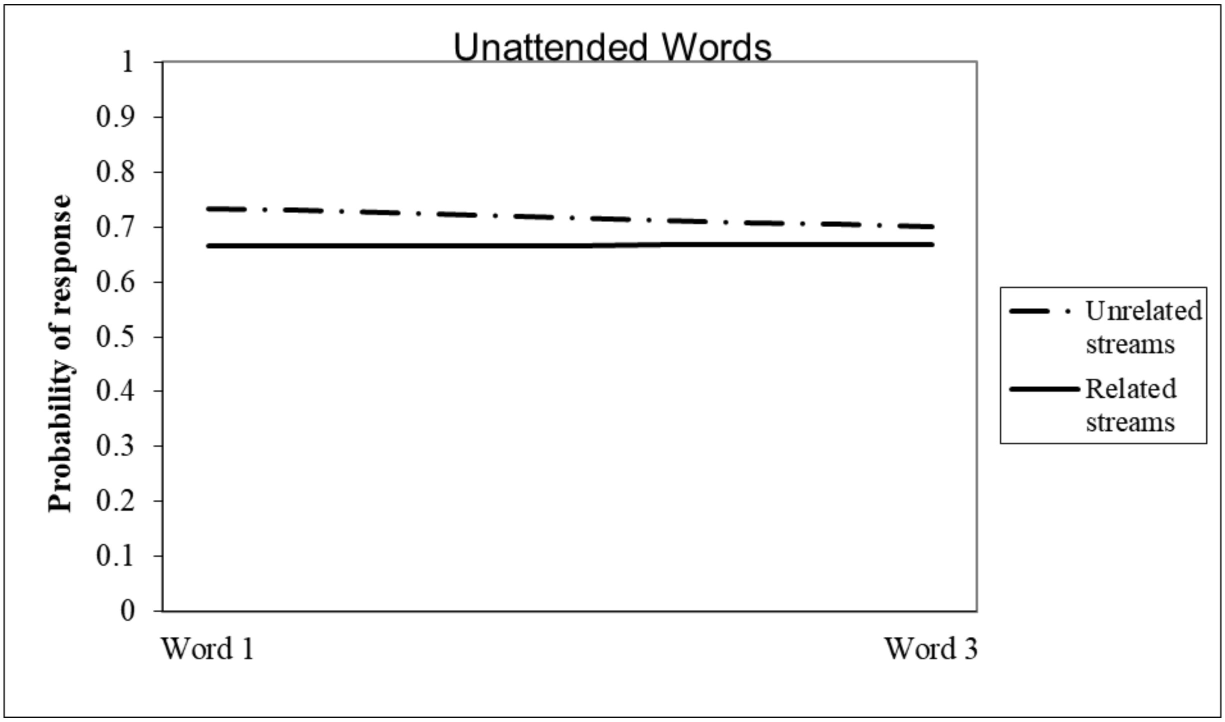

Figure 24: Interaction of stream relatedness with learning effect on accuracy in unattended stream

Age did not interact with the learning effect on any measure in either stream (Unattended RT: t=.568, p=.572 and accuracy: z=-1.177, p=.239; Attended RT: t=-1.947, p=.056 and accuracy: z=-1.859, p=.063). This is counter to the predictions of both the ADH and the HBH, which would predict older adults to have reliably weaker learning effects than younger adults, at least for attended words, but it is consistent with the findings of Experiment IIa which also failed to find a reliable age effect.

Age and triplet relatedness interacted with learning effect on RT for attended words (t=-2.685, p=.007), indicating that the facilitative effect of triplet relatedness on learning the attended stream was stronger for older participants than younger ones, as expected based on the predictions of the HBH, but not the ADH (which would predict this pattern only for pre-existing relationships between known words.)

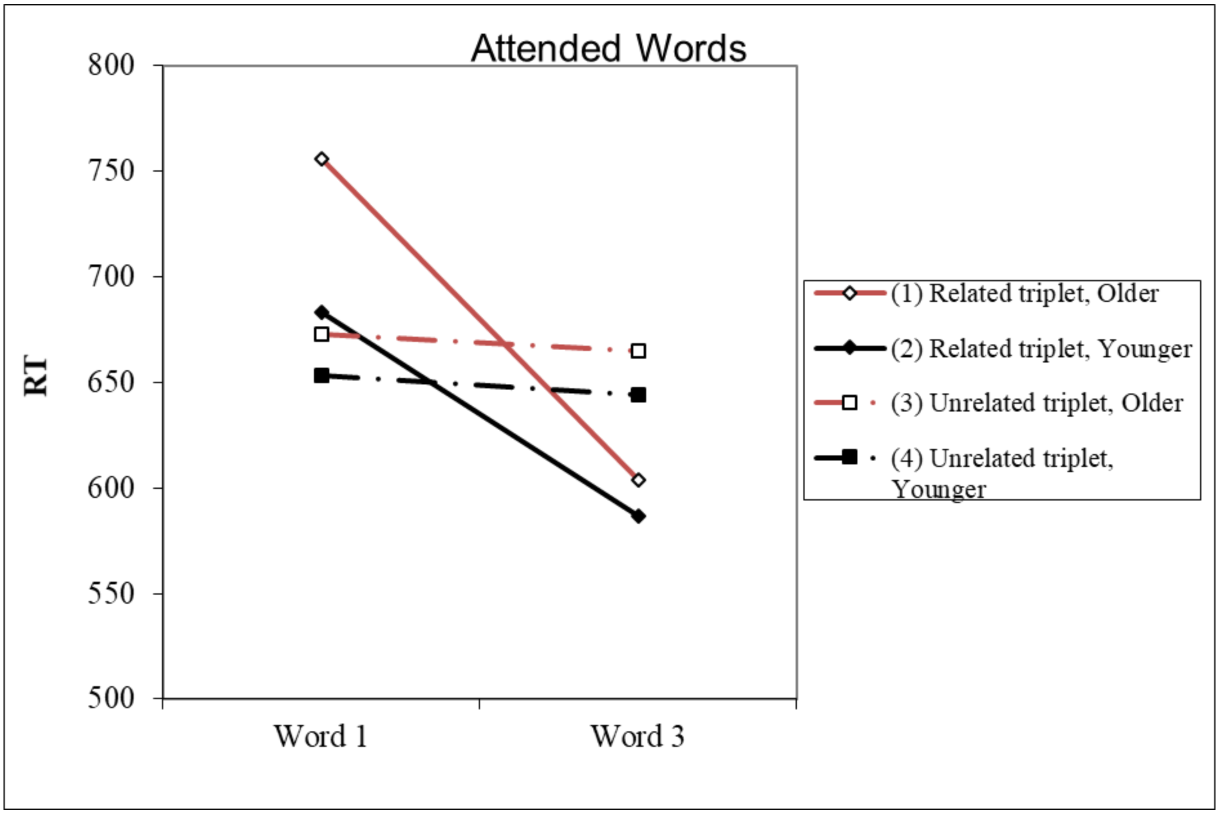

Figure 25: Interaction of triplet relatedness, age group, and learning effect on RT in attended stream

This interaction was not present in the unattended stream (t=1.465, p=.193), nor in the accuracy data for the attended stream (z=-.751, p=.452), although it approached significance in the unattended stream (Unattended: z=-1.971, p=.049), in which triplet relatedness negatively affected older adults' performance and facilitated younger adults' performance, and these age differences were smaller for unrelated triplets. This is again consistent with an interference-based interpretation, and should be explored further in future studies.

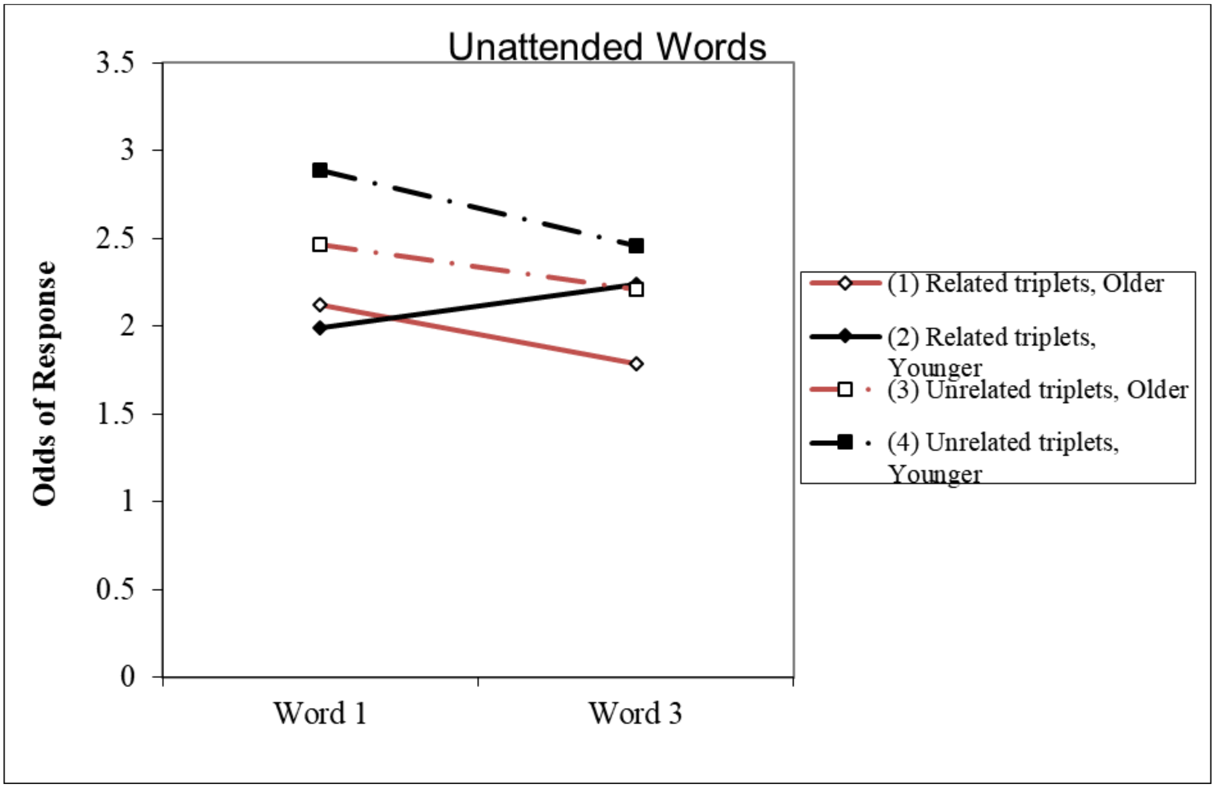

Figure 26: Interaction of triplet relatedness, age group, and learning effect on response accuracy in unattended stream

The three-way interaction of age, stream relatedness, and learning effect was nonsignificant for attended words (RT: t=.387, p=.699; accuracy: z=-1.299, p=.194) and in the RT data for unattended words (RT: t=.384, p=.572), although it approached significance in the accuracy data for unattended words (z=-2.071, p=.038). Like the interaction between age, triplet relatedness, and learning, this pattern reflects a larger age difference in the related than in the unrelated condition, supporting an interference-based interpretation.

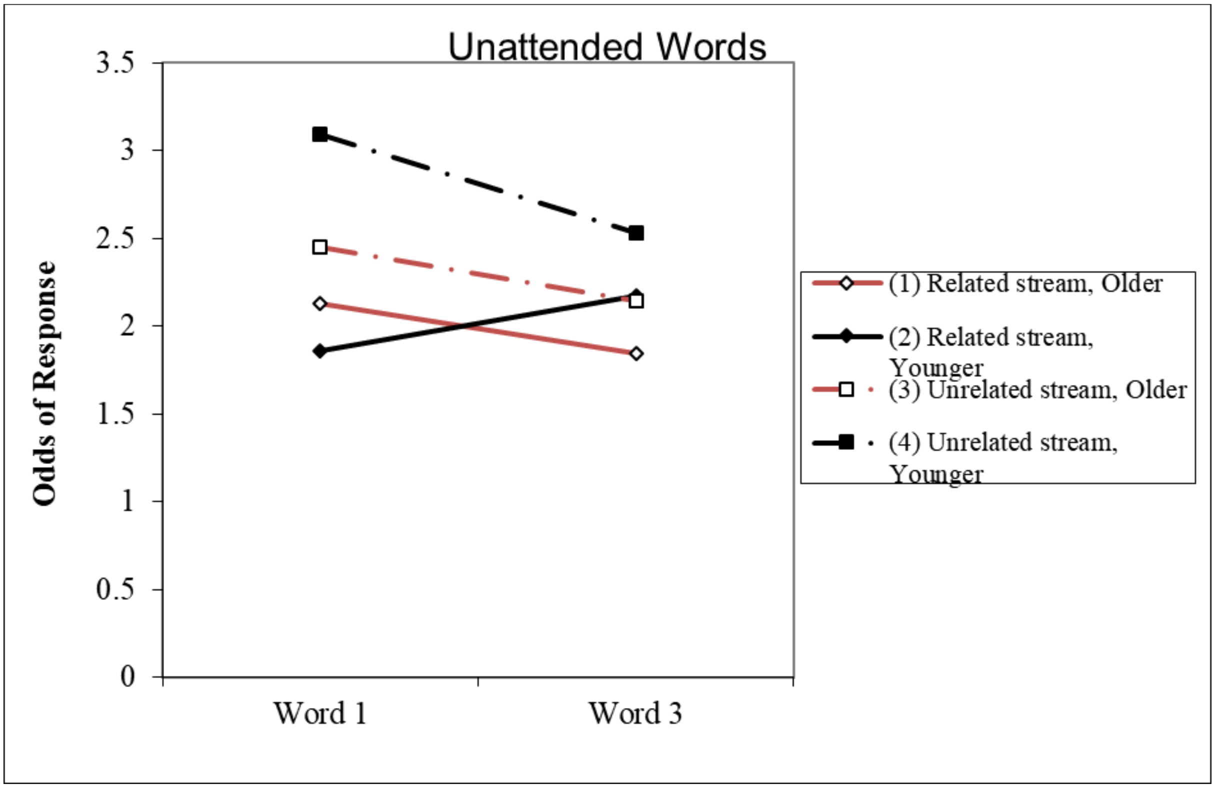

Figure 27: Interaction of stream relatedness, age group, and learning effect on response accuracy in unattended stream

The three-way interaction of age, stream attendance, and learning effect (as determined by the larger, combined model) was significant in the RT data (t=2.828, p=.005) but not in the accuracy data (z=.427, p=.669). The data indicates a similar learning effect for older and younger participants on unattended words, but a larger learning effect for older than for younger participants on attended words. Critically, this effect cannot be accounted for by the ADH, as it would predict that younger adults should outperform older participants in any context. Counter to the HBH, though, younger participants appear to have roughly equivalent learning effects across the two streams, whereas the older adults appear to have a reduced learning effect in the unattended stream as compared to the attended stream.

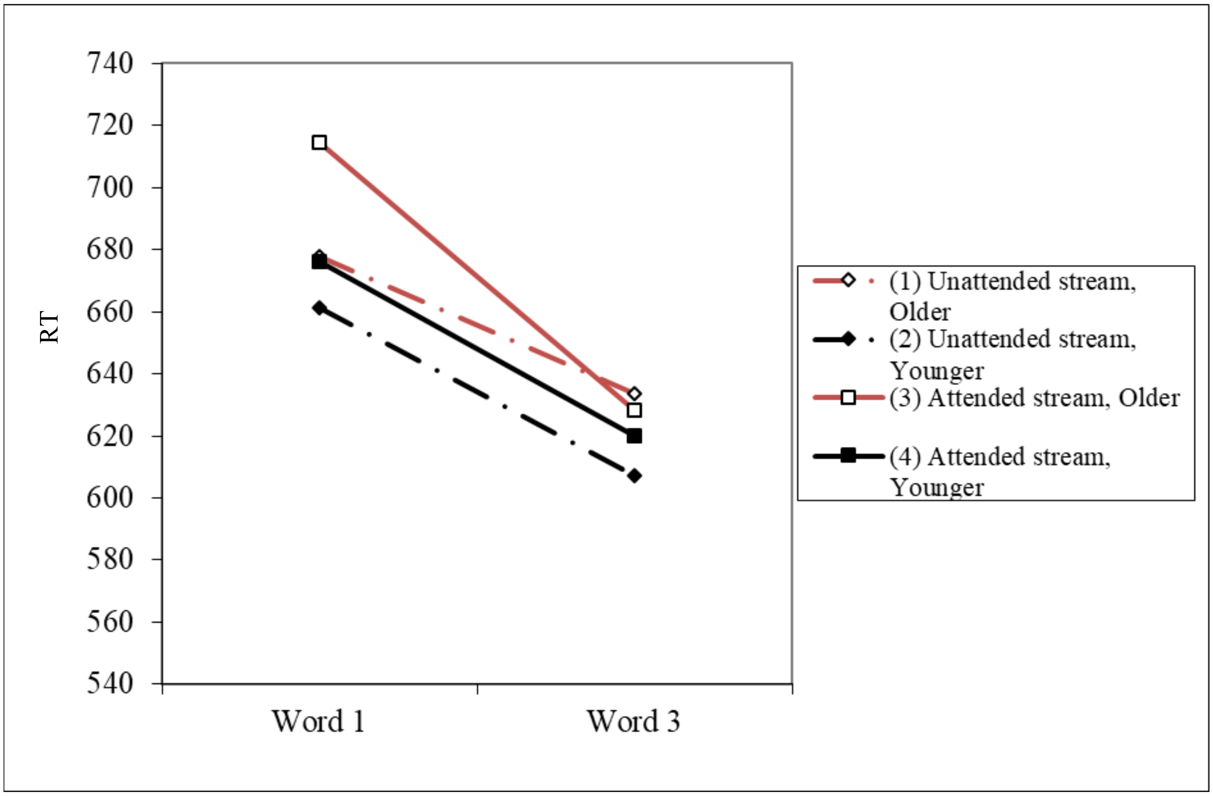

Figure 28: Interaction of stream attendance, age group, and learning effect on RT

This three-way interaction was not affected by stream relatedness, as indicated by the nonsignificant four-way interaction of learning effect, stream attendance, stream relatedness, and age (t=-.159, p=.873), indicating that the similarity manipulation did not create differing levels of interference across age groups. Triplet relatedness did, however, amplify the age-related difference in stream attendance effects on learning (t=2.92, p=.004), such that the difference was much larger for related triplets than for unrelated triplets. Neither four-way interaction was significant in the accuracy data (z=-.506, p=.613 and z=-.913, p=.361, respectively).

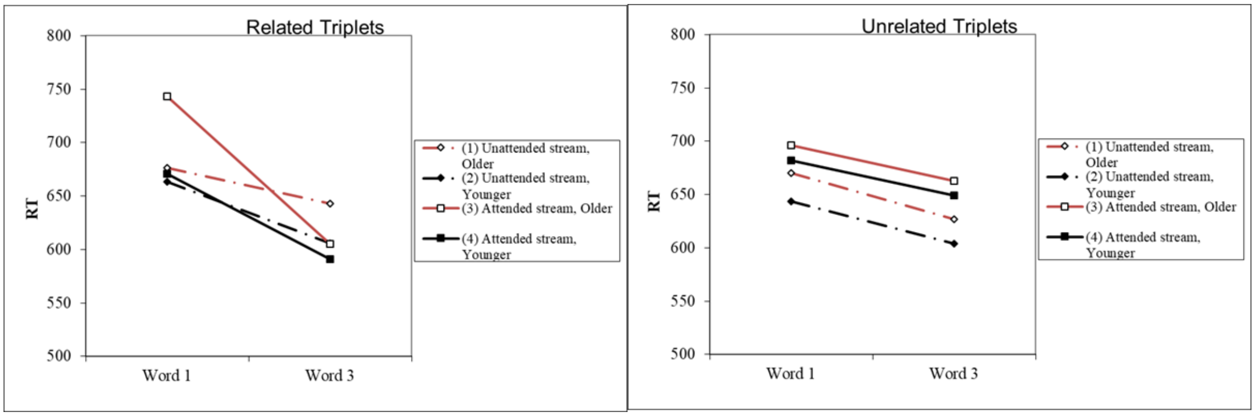

Figure 29: Interaction of stream attendance, age group, and learning effect on RT in related and unrelated triplets

5.0 Experiments I and II: Participant awareness/ "implicitness" measure

Following the completion of all experimental tasks, participants were informally interviewed about the experiment they had just completed. These interviews were not intended to contribute to the statistical analysis of either experiment, but rather to guide interpretation of results and provide qualitative insight into the participants' conscious awareness of the task characteristics. Since the experiments included heavily-modified or novel tasks, this data may provide guidance on how future studies might improve upon these protocols.

The order in which participants completed the experiments was counterbalanced, so that roughly half of those who completed both experiments were interviewed about Experiment I, and half about Experiment II. Since some participants only completed one of the experiments, however, the sample sizes are different for the two experiments. Interviews were de-identified at the time of recording, so some participants that were eventually excluded from analyses based on equipment malfunction or exclusionary criteria were included in these interviews. As the interviews were intended to elaborate on the range of participants' subjective experiences of the tasks, it is unlikely that these inclusions should have any important effects.

Each participant was reminded that there were two parts to the experiment they just completed (the training and the testing portions, although they were not referred to as such in the interview,) and the parts were described. The participant was then asked what strategies, if any, they used during the "second part" (i.e. the testing phase,) and whether they had noticed any patterns or connections between the two parts. These interviews were recorded and the responses were coded by two independent judges.

For Experiment I, participants were coded as having mentioned the pictures' backgrounds as a source of information or not. For Experiment II, participants were coded as having noticed a pattern in the words or not. This coding was performed by two independent judges with 98.5% agreement for Experiment I and 91.4% agreement for Experiment II.

Participants in Experiment I overwhelmingly focused on the relationship between the objects and the novel pseudowords, with only 2 (Judge #1) or 3 (Judge #2) of the 67 people interviewed mentioning the images' backgrounds as having been informative. This is a strong indicator that participants were unaware of the context frequency manipulation, suggesting that this associative binding would have been performed implicitly.

Participants in Experiment II, by contrast, overwhelmingly noticed the pattern in the words, with 77 (Judge #1) or 70 (Judge #2) of the 81 interviews indicating that a pattern had existed in the stimuli. Follow-up questioning by the experimenter revealed that participants noticed a pattern more often in the speeded-detection task. Of those questioned, 36 (Judge #1) or 37 (Judge #2) participants thought that the same pattern was present in the training task as the speeded-detection task. Given that the interviews were completely de-identified, group-level analysis of pattern awareness is not possible, but since such an overwhelming majority reported some awareness of a pattern, it is unlikely that any significant age-related differences in base pattern awareness occurred, although the perception that the pattern was the same across the tasks may have varied with age.

These results suggest that the relationships in Experiment II, while an effective test of associative binding, were probably not learned implicitly by the majority of the participants. This makes our findings from Experiment II, which lack a consistent age effect on learning, particularly surprising. Given that intentional, goal-driven learning is thought to be more influenced by age than implicit learning is (e.g. Song et al., 2009), we would expect that explicit learning behaviors should exaggerate any underlying age-related learning differences.

6.0 Discussion

Experiments I and II were designed to test age differences in two different types of associative binding. Experiments Ia and Ib tested context dependence of learned relationships and found no reliable difference between younger and older adults' response to context frequency manipulations, which is counter to the predictions of both the ADH and the HBH. Such a finding is not unprecedented within IL literature; Howard et al. (2004) found age-invariance in a contextual cueing task, and suggested that this finding may reflect the fact that different neural substrates appear to be responsible for contextual cueing than are responsible for sequence learning. This research reflects specifically spatial learning in the absence of semantic content, however; when Kessels et al. (2007) tested memory for objects' position and order of appearance within a grid, they found that older adults performed significantly worse, and suggested that the process of binding features of an object to its context is deteriorated in older individuals. Thus, it is somewhat surprising to find age-invariance during the task in Experiment I, which tested memory for the target object's positioning within a meaningful context.

Further investigation of this question is necessary, as indicated by the size and direction of the effect estimates for the three- and four-way interactions in the RT data. The pattern of these interactions is consistent with the predictions of the HBH, wherein older adults should have been more dependent on context than younger adults following unblurred training and this difference should be smaller following blurred training. It seems that the large variance present within the RT data is responsible for its lack of reliability rather than a small effect size. In this case, future studies with more tightly-controlled participant characteristics and/or more trials may find these patterns to be statistically reliable. This finding highlights the fact that the existing literature regarding aging and associative binding has been developed using comparisons across groups of participants that are unequal in terms of age range and variability. While the current studies have been designed to replicate these participant groups, future investigations should distinguish between phases of later life, since significant differences in the extent of age-related cognitive changes have been observed between those aged 60-69 and those aged 70-79 (Garfein & Herzog, 1995).

Experiments IIa and IIb also showed surprising age-invariance in the base measure of learning (the effect of Triplet Position on RT and accuracy). Unlike Experiments Ia and Ib, this experiment tested binding of serial items using an alternating presentation sequence, which should have maximized the task's sensitivity to aging effects based on previous findings (e.g. Dennis et al., 2003; Feeney et al., 2002; D. V. Howard et al., 2004).

The findings of Badham and Maylor (2011) suggest that age-related associative differences may be absent or reduced for pseudowords compared to real words due to differing neural substrates supporting processing of each, but the basic Learning x Age interaction was absent for both in our tasks. Given the length of the task and the number of repetitions of each triplet, over-learning of the relationships is a tempting explanation. However, given findings that older adults benefit less than younger adults from repetition of associations (Overman & Becker, 2009), the number of repetitions should have exaggerated any underlying age differences in learning. The general level of accuracy suggests against ceiling or floor effects: Older adults responded to target words with 65% and 76% accuracy in Experiment IIa and IIb, respectively, and younger adults responded with 68% and 78% accuracy. Unlike in Experiments Ia and Ib, the effect size estimates of these interactions in the RT data are relatively small, so it is less clear whether reducing the age range of the older group is likely to provide a sufficient reduction in variance to make these effects reliable. The absence of a straightforward Learning x Age interaction is counter to the predictions of both the HBH and the ADH, and means that neither model can satisfactorily account for the entire set of findings.

That established, the HBH is somewhat more consistent with the Experiment IIa-b data than the ADH. The Learning effect x Age x Triplet relatedness interaction on response accuracy in the Attended stream of Experiment IIa showed that semantically-related triplets facilitated younger adults' learning more than older adults', whereas the same interaction on RT in the Attended stream of Experiment IIb showed that phonologically-related triplets facilitated older adults' learning more than younger adults' learning. The ADH would predict the opposite, that a pre-existing semantic relationship should facilitate older adults relative to younger adults more than a novel phonological relationship between pseudowords. Although the HBH does not specifically predict this pattern of results, it could accommodate them by postulating that when no stored relationships exist, older adults experience less interference and are more facilitated by the perceptual similarity of the stimuli, compared to the semantic similarities which require accessing stored relationships that are vulnerable to interference by other near semantic neighbors. One way to test this hypothesis would be to have participants complete the same task using as stimuli English words that are phonologically similar but are not semantically related. These would be vulnerable to the same interference through access of the semantic network, but would have the perceptual similarity that appears to have facilitated older adults' learning so effectively in Experiment IIb.

Tentative support for the HBH also comes from the Learning x Age x Stream relatedness interaction on RT in the Attended stream of Experiment IIa. This interaction was not statistically reliable after adjusting for multiple comparisons, but its direction suggested that older adults learned better when streams were unrelated whereas younger adults were less affected by stream relatedness, a critical prediction of the HBH. A future study might manipulate cross-stream relatedness in the absence of the triplet-relatedness manipulation and use a less-varied older age group to reduce the noise in the data.

Some of the findings are inconsistent with the HBH, however. The interaction of age and stream attendance on learning effect in Experiment IIb, which addresses the central hypothesis of the HBH, was in the opposite direction from what the HBH would predict: younger adults were unaffected by stream attendance relative to older adults, who performed better than younger adults in the attended stream and worse in the unattended stream. Neither experiment revealed an interaction of age, stream attendance, and stream relatedness on learning effect, which should have been present if the HBH is to account for all of the observed data. Finally, the four-way interaction of age, stream attendance, triplet relatedness, and learning effect was in the opposite direction of what would have been predicted by the HBH.

Post-experimental interviews revealed that the contextual manipulation in Experiment I were likely learned implicitly by the majority of participants, whereas the triplet groupings in Experiment II were at least partially consciously noticed during learning by a sizeable fraction of the participant group. This awareness seems to have been encouraged by the speeded-detection task, wherein the triplets were repeated in relatively quick succession (similar to the issues with "implicitness" observed in blocked SRT designs.) If future studies hope to induce a more implicit learning process with this task, they might eliminate the within-triplet similarity manipulation to reduce the saliency of the triplet groups and/or avoid having participants complete multiple training and testing blocks in succession, to reduce the noticeability of the patterns involved. Despite its lack of implicitness in the current study, the results are indicative of associative binding, and still serve to examine whether or not the different AB-based accounts of learning can explain the aging patterns observed in the IL literature.

In combination, these studies do not strongly support either the HBH or the ADH as comprehensive accounts of AB in older adults, particularly because older adults did not demonstrate significantly reduced binding behaviors in either task. The data does show some evidence that when age differences are observed, they tend to be in ways that are more easily explained by interference and/or dysregulation than a simple deficit in the ability to bind information (see Table 3 for a brief summary of the evidence that is and is not accounted for by each model.)

As described previously in this section, further work is necessary to examine why these experiments did not elicit the age differences that have been observed by previous researchers, and to further explore the patterns of interactions that were observed. By using a more tightly-constrained older age group, the wide RT variances may be reduced making null results easier to interpret. Modifying the protocol from Experiment II to remove the within-stream relatedness manipulation may also reduce the overall noise in the data and allow for cleaner comparisons. Using real-word stimuli with phonological similarities and semantic dissimilarities may confirm or refute the semantic interference-based account of the differences in the Triplet relatedness x Age x Learning effect interactions from Experiments IIa and IIb. Finally, avoiding repeated exposure to the speeded-detection task may reduce the explicitness of the Experiment II protocol, allowing these results to reflect associative binding specifically within an IL context as opposed to more generally.

These steps will provide a foundation for further exploration of the apparent contradiction of IL's relative age-invariance in the context of age-related declines in fluid intelligence. Future directions in this line of inquiry should involve comparing appropriately reliable measures of fluid intelligence markers, such as selective attention and processing speed (c.f. Salthouse et al., 1999), to these AB-related protocols. Situating the competing models of AB within the larger cognitive aging context, and comparing their predictions (the HBH predicts an inverse correlation between fluid intelligence and AB, whereas the ADH predicts either no correlation or a positive relationship), we should gain further insight into this question.

Table 3: Summary of evidence that is or is not accounted for by each AB model

	ADH	HBH	Both
Evidence accounted for	**Experiment IIa:** • No interaction between age and learning effect in Unattended stream	**Experiments Ia and Ib:** • Nonsignificant trends in data toward a reduction in age differences following blurred training versus unblurred training **Experiment IIa:** • Within-triplet semantic relatedness facilitated younger adults more than older adults (interference-based account) **Experiment IIb:** • Within-triplet phonological relatedness facilitated older adults more than younger adults (interference-based account) • Interaction between stream relatedness, age, and learning effect approached significance	**Experiments Ia and Ib:** • Increased RTs and decreased accuracy overall on task for older adults **Experiment IIa:** • Trend toward reduced learning effect in RT for Attended stream for older adults
Evidence not accounted for	**Experiment IIa:** • Within-triplet semantic relatedness facilitated younger adults more than older adults **Experiment IIb:** • Within-triplet phonological relatedness facilitated older adults more than younger adults	**Experiment IIa:** • Younger adults learned unattended relationships better than older adults when triplets were unrelated • No significant interaction between stream relatedness, age, and learning effect	**Experiments Ia and Ib:** • No significant effect of age on measures of context dependence **Experiments IIa and IIb:** • No significant interaction of age with learning effect **Experiment IIb:** • Stream attendance affected older adults more than younger adults; older adults learned better than younger adults in attended stream

Appendix A

Model Results

This Appendix contains the model results in table format for each of the above-described experiments. Significant effects following Type I error correction are denoted with an asterisk; nonsignificant effects of p<.05 are denoted with a period. Interactions of interest (i.e. those that included the learning effect) in Experiment II are highlighted.

Table 4: Reaction time models for Experiments Ia and Ib

RT Model: Experiment Ia (Unblurred Training)						
Formula: RT ~ AgeGroup * Masking * ContextFreq+(1+Masking+ContextFreq|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Participant	(Intercept)	501691.4	708.3			
	Masking1	197666.7	444.6	0.06		
	ContextFreq1	778.8	27.91	-0.64	-0.81	
Item	(Intercept)	60467	245.9			
Residual		1462320	1209.26			
Number of obs: 1323, groups: Participant, 57; Item, 6						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	2785.53	141.41	14.9	19.698	4.45E-12	*
AgeGroup1	788.53	199.19	54.88	3.959	0.000219	*
Masking1	340.24	88.98	53.84	3.824	0.000343	*
ContextFreq1	-180.82	66.74	1019.43	-2.71	0.006851	*
AgeGroup1:Masking1	-212.99	177.97	53.84	-1.197	0.236646	
AgeGroup1:ContextFreq1	-260.74	133.48	1019.64	-1.953	0.051049	
Masking1:ContextFreq1	441.2	133.29	1201.76	3.31	0.000961	*
AgeGroup1:Masking1:ContextFreq1	-459.63	266.6	1201.8	-1.724	0.084952	

RT Model: Experiment Ib (Blurred Training)						
Formula: RT ~ AgeGroup * Masking * ContextFreq+(1+Masking+ContextFreq|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Participant	(Intercept)	689698	830.48			
	Masking1	26771	163.62	0.4		
	ContextFreq1	1897	43.56	-0.92	-0.01	
Item	(Intercept)	46039	214.57			
Residual		1405805	1185.67			
Number of obs: 1486, groups: Participant, 63; Item, 6						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	2576.99	140.42	22.55	18.352	4.76E-15	*
AgeGroup1	1037.28	219.5	61.06	4.726	1.39E-05	*
Masking1	32.36	65.36	61.97	0.495	0.622256	
ContextFreq1	-166.03	62.21	936.95	-2.669	0.007741	*
AgeGroup1:Masking1	12.16	130.73	61.97	0.093	0.926159	
AgeGroup1:ContextFreq1	48.63	124.42	936.91	0.391	0.695989	
Masking1:ContextFreq1	470.17	123.95	1352.16	3.793	0.000155	*
AgeGroup1:Masking1:ContextFreq1	114.45	247.9	1352.16	0.462	0.644371	

RT Model: Experiments Ia and Ib RT~AgeGroup* Masking* ContextFreq* Training+ (1+Masking+ContextFreq|Participant)+(1+ContextFreq+Masking|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Participant	(Intercept)	605631	778.22			
	Masking1	118625	344.42	0.13		
	ContextFreq1	1070	32.72	-0.99	-0.26	
Item	(Intercept)	53552	231.41			
	ContextFreq1	153600	391.92	-0.54		
	Masking1	131160	362.16	-0.75	0.84	
Residual		1368316	1169.75			
Number of obs: 2809, groups: Participant, 120; Item, 6						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	2682.909	120.46	11.698	22.272	6.09E-11	*
AgeGroup1	921.447	149.47	116.051	6.165	1.06E-08	*
Masking1	183.718	157.583	5.428	1.166	0.29233	
ContextFreq1	-177.404	166.08	5.01	-1.068	0.33418	
Training1	-207.726	149.467	116.042	-1.39	0.16726	
AgeGroup1:Masking1	-113.624	109.049	114.009	-1.042	0.29964	
AgeGroup1:ContextFreq1	-119.352	89.054	2116.243	-1.34	0.18032	
Masking1:ContextFreq1	462.566	88.862	2548.153	5.205	2.09E-07	*
AgeGroup1:Training1	243.231	298.934	116.042	0.814	0.41751	
Masking1:Training1	-307.148	109.033	113.948	-2.817	0.00571	*
ContextFreq1:Training1	16.197	89.04	2116.052	0.182	0.85568	
AgeGroup1:Masking1:ContextFreq1	-143.625	177.738	2548.172	-0.808	0.41912	
AgeGroup1:Masking1:Training1	227.777	218.066	113.949	1.045	0.29845	
AgeGroup1:ContextFreq1:Training1	309.294	178.08	2116.043	1.737	0.08256	
Masking1:ContextFreq1:Training1	28.875	177.702	2548.039	0.162	0.87093	
AgeGroup1:Masking1: ContextFreq1:Training1	558.667	355.414	2548.06	1.572	0.1161	

Table 5: Accuracy models for Experiments Ia and Ib

Accuracy Model: Experiment Ia (Unblurred Training)					
Formula: ACC ~ AgeGroup * Masking * ContextFreq+(1+Masking|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Participant	(Intercept)	2.325	1.5248		
	Masking1	1.712	1.3084	-1	
Item	(Intercept)	0.2799	0.5291		
Number of obs: 1323, groups: Participant, 57; Item, 6					
Fixed effects:					
	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.841	0.3306	5.569	2.56E-08	*
AgeGroup1	-1.1499	0.4601	-2.499	0.012452	.
Masking1	-1.8395	0.3342	-5.504	3.72E-08	*
ContextFreq1	-0.5521	0.1646	-3.353	0.000799	*
AgeGroup1:Masking1	0.6082	0.5331	1.141	0.253895	
AgeGroup1:ContextFreq1	-0.1992	0.3287	-0.606	0.544469	
Masking1:ContextFreq1	-0.2134	0.3293	-0.648	0.517017	
AgeGroup1:Masking1:ContextFreq1	0.2246	0.6564	0.342	0.732222	

Accuracy Model: Experiment Ib (Blurred Training)					
Formula: ACC ~ AgeGroup * Masking * ContextFreq+(1+Masking+ContextFreq|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Participant	(Intercept)	4.7868	2.1879		
	Masking1	0.6982	0.8356	-0.96	
	ContextFreq1	0.6305	0.794	-0.97	1
Item	(Intercept)	0.1505	0.3879		
Number of obs: 1486, groups: Participant, 63; Item, 6					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.8614	0.349	5.333	9.65E-08	*
AgeGroup1	-1.253	0.6011	-2.084	0.03712	.
Masking1	-0.7546	0.2511	-3.006	0.002651	*
ContextFreq1	-0.863	0.2474	-3.488	0.000486	*
AgeGroup1:Masking1	0.8802	0.3992	2.205	0.027447	.
AgeGroup1:ContextFreq1	0.8003	0.3909	2.047	0.040636	.
Masking1:ContextFreq1	0.102	0.2948	0.346	0.729241	
AgeGroup1:Masking1:ContextFreq1	-0.1338	0.5792	-0.231	0.817259	

Accuracy Model: Experiments Ia and Ib

Formula: ACC ~ AgeGroup * Masking * ContextFreq * Training+(1+Masking|Participant)+(1+ContextFreq+Masking|Item)

Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Participant	(Intercept)	3.2595	1.8054		
	Masking1	1.0991	1.0484	-1	
Item	(Intercept)	0.2022	0.4496		
	ContextFreq1	0.1128	0.3359	-0.14	
	Masking1	0.1626	0.4032	0.05	0.98
Number of obs: 2809, groups: Participant, 120; Item, 6					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.768871	0.262581	6.736	1.62E-11	*
AgeGroup1	-1.162068	0.361968	-3.21	0.00133	*
Masking1	-1.293071	0.254364	-5.084	3.70E-07	*
ContextFreq1	-0.460081	0.174168	-2.642	0.00825	.
Training1	-0.059413	0.359893	-0.165	0.86888	
AgeGroup1:Masking1	0.791917	0.31725	2.496	0.01255	.
AgeGroup1:ContextFreq1	0.115376	0.214212	0.539	0.59016	
Masking1:ContextFreq1	-0.122263	0.214436	-0.57	0.56857	
AgeGroup1:Training1	-0.005674	0.719242	-0.008	0.99371	
Masking1:Training1	0.662867	0.305397	2.171	0.02997	.
ContextFreq1:Training1	0.223364	0.214071	1.043	0.29676	
AgeGroup1:Masking1:ContextFreq1	0.038957	0.427702	0.091	0.92743	
AgeGroup1:Masking1:Training1	0.563282	0.611279	0.921	0.3568	
AgeGroup1:ContextFreq1:Training1	0.572154	0.42811	1.336	0.1814	
Masking1:ContextFreq1:Training1	0.245742	0.427355	0.575	0.56527	
AgeGroup1:Masking1: ContextFreq1:Training1	-0.221872	0.854802	-0.26	0.7952	

Table 6: RT Models for Experiment IIa

RT Model: Experiment IIa, Attended Stream Formula: RT ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Item	(Intercept)	753.4	27.45			
Participant	(Intercept)	5555.5	74.54			
	TripletMemberc	1642.7	40.53	-0.04		
	TripletRel1	1934.6	43.98	0.04	0.53	
Residual		21846.4	147.81			
Number of obs: 8734, groups: Item, 60; Participant, 59						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	583.995	10.715	73.131	54.505	< 2e-16	*
TripletMemberc	-89.338	6.855	85.767	-13.032	< 2e-16	*
AgeGroup1	63.048	19.971	56.965	3.157	0.00255	*
ripletRel1	-10.226	8.195	135.39	-1.248	0.21425	
StreamRel1	-6.743	4.634	8597.856	-1.455	0.1457	
TripletMemberc:AgeGroup1	30.028	12.358	57.291	2.43	0.01826	.
TripletMemberc:TripletRel1	-41.212	8.444	1222.283	-4.881	1.20E-06	*
AgeGroup1:TripletRel1	16.771	14.693	89.55	1.141	0.25672	
TripletMemberc:StreamRel1	7.413	6.464	8589.792	1.147	0.25146	
AgeGroup1:StreamRel1	-24.74	9.157	8528.24	-2.702	0.00691	*
TripletRel1:StreamRel1	-9.702	9.271	8594.539	-1.046	0.29539	
TripletMemberc:AgeGroup1:TripletRel1	16.904	12.768	8532.971	1.324	0.18556	
TripletMemberc:AgeGroup1:StreamRel1	25.215	12.756	8525.589	1.977	0.04812	.
TripletMemberc:TripletRel1:StreamRel1	49.485	12.926	8585.771	3.828	0.00013	*
AgeGroup1:TripletRel1:StreamRel1	-14.85	18.312	8528.099	-0.811	0.41743	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-33.925	25.502	8519.258	-1.33	0.18346	

RT Model: Experiment IIa, Unattended Stream

Formula: RT ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)

Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Participant	(Intercept)	5526.4	74.34		
	TripletMemberc	746.3	27.32	-0.2	
	TripletRel1	1171.6	34.23	0.03	0.11
Item	(Intercept)	488	22.09		
Residual		21746.6	147.47		

Number of obs: 8563, groups: Participant, 59; Item, 55

Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	593.709	10.513	69.242	56.472	< 2e-16	*
TripletMemberc	-63.033	5.412	85.493	-11.648	< 2e-16	*
AgeGroup1	66.776	19.929	56.992	3.351	0.00144	*
TripletRel1	-10.807	7.348	170.438	-1.471	0.14324	
StreamRel1	-13.499	4.652	8426.667	-2.902	0.00372	*
TripletMemberc:AgeGroup1	14.519	9.616	54.38	1.51	0.13688	
TripletMemberc:TripletRel1	-41.152	8.854	597.538	-4.648	4.13E-06	*
AgeGroup1:TripletRel1	9.161	12.861	106.362	0.712	0.47784	
TripletMemberc:StreamRel1	-8.356	6.499	8418.532	-1.286	0.19852	
AgeGroup1:StreamRel1	-8.931	9.224	8376.884	-0.968	0.33299	
TripletRel1:StreamRel1	-5.684	9.313	8426.258	-0.61	0.54167	
TripletMemberc:AgeGroup1:TripletRel1	10.056	12.881	8386.715	0.781	0.43503	
TripletMemberc:AgeGroup1:StreamRel1	7.575	12.868	8376.386	0.589	0.55609	
TripletMemberc:TripletRel1:StreamRel1	-4.73	13.01	8417.962	-0.364	0.7162	
AgeGroup1:TripletRel1:StreamRel1	22.231	18.455	8375.514	1.205	0.22839	
TripletMemberc:AgeGroup1: TripletRel1:StreamRel1	-4.306	25.738	8374.037	-0.167	0.86713	

RT Model: Experiment IIa, Both Streams

Formula: RT ~ TripletMember * AgeGroup * Stream * TripletRel * StreamRel+(1+TripletMember+Stream|Participant)+(1|Item)

Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Item	(Intercept)	291.7	17.08		
Participant	(Intercept)	5535.8	74.4		
	Triplet Memberc	1026.2	32.03	-0.08	
	Stream1	131.1	11.45	-0.17	-0.54
Residual		22443.5	149.81		

Number of obs: 17297, groups: Item, 69; Participant, 59

Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	586.338	10.091	62.828	58.107	< 2e-16	*
TripletMemberc	-73.404	5.007	69.668	-14.661	< 2e-16	*
AgeGroup1	65.441	19.678	56.995	3.326	0.00155	*
Stream1	11.471	4.019	255.933	2.854	0.00466	*
TripletRel1	-5.458	3.58	8076.491	-1.524	0.12748	
StreamRel1	-11.196	3.301	17135.383	-3.392	0.0007	*
TripletMemberc:AgeGroup1	21.566	9.542	57.567	2.26	0.0276	.
TripletMemberc:Stream1	21.189	5.041	7263.368	4.204	2.66E-05	*
AgeGroup1:Stream1	4.383	7.22	172.372	0.607	0.54464	
TripletMemberc:TripletRel1	-47.171	5.287	4141.706	-8.923	< 2e-16	*
AgeGroup1:TripletRel1	11.502	6.582	17094.106	1.748	0.08057	
Stream1:TripletRel1	2.991	7.612	3812.031	0.393	0.69441	
TripletMemberc:StreamRel1	1.236	4.614	17149.418	0.268	0.78884	
AgeGroup1:StreamRel1	-16.937	6.576	17072.25	-2.575	0.01002	.
Stream1:StreamRel1	-6.486	6.611	17143.271	-0.981	0.32659	
TripletRel1:StreamRel1	-9.749	6.605	17139.724	-1.476	0.13995	
TripletMemberc:AgeGroup1:Stream1	-15.149	9.169	17076.834	-1.652	0.09851	
TripletMemberc:AgeGroup1:TripletRel1	13.636	9.185	17109.376	1.485	0.13765	
TripletMemberc:Stream1:TripletRel1	-9.636	10.824	3047.579	-0.89	0.37342	
AgeGroup1:Stream1:TripletRel1	-6.883	13.149	17091.386	-0.523	0.60067	
TripletMemberc:AgeGroup1:StreamRel1	15.919	9.179	17088.208	1.734	0.08287	
TripletMemberc:Stream1:StreamRel1	-17.256	9.233	17110.134	-1.869	0.06165	
AgeGroup1:Stream1:StreamRel1	15.456	13.143	17086.849	1.176	0.23962	
TripletMemberc:TripletRel1:StreamRel1	25.708	9.229	17158.808	2.786	0.00535	*
AgeGroup1:TripletRel1:StreamRel1	3.824	13.159	17077.258	0.291	0.77139	
Stream1:TripletRel1:StreamRel1	2.971	13.233	17141.957	0.224	0.82238	
TripletMemberc:AgeGroup1: Stream1:TripletRel1	-9.428	18.348	17065.467	-0.514	0.60737	
TripletMemberc:AgeGroup1: Stream1:StreamRel1	-16.929	18.342	17064.006	-0.923	0.35603	
TripletMemberc:AgeGroup1: TripletRel1:StreamRel1	-18.574	18.36	17094.197	-1.012	0.31171	
TripletMemberc:Stream1: TripletRel1:StreamRel1	-56.808	18.479	17112.37	-3.074	0.00211	*
AgeGroup1:Stream1: TripletRel1:StreamRel1	41.019	26.285	17086.559	1.561	0.11865	
TripletMemberc:AgeGroup1: Stream1:TripletRel1:StreamRel1	26.756	36.683	17065.142	0.729	0.46578	

Table 7: Accuracy Models for Experiment IIa

Accuracy Model: Experiment IIa, Attended Stream Formula: Response ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Item	(Intercept)	0.14145	0.3761		
Participant	(Intercept)	0.22122	0.4703		
	TripletMemberc	0.09308	0.3051	0.07	
	TripletRel1	0.08697	0.2949	-0.61	0.45
Number of obs: 11232, groups: Item, 60; Participant, 59					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.19081	0.0881	13.516	< 2e-16	*
TripletMemberc	0.38973	0.07687	5.07	3.97E-07	*
AgeGroup1	-0.09484	0.13878	-0.683	0.49439	
TripletRel1	-0.04568	0.09086	-0.503	0.61517	
StreamRel1	0.05493	0.06462	0.85	0.39529	
TripletMemberc:AgeGroup1	-0.24215	0.12558	-1.928	0.05382	
TripletMemberc:TripletRel1	0.51457	0.12582	4.09	4.32E-05	*
AgeGroup1:TripletRel1	0.08771	0.15003	0.585	0.55879	
TripletMemberc:StreamRel1	-0.08538	0.09612	-0.888	0.37441	
AgeGroup1:StreamRel1	0.04011	0.1279	0.314	0.75382	
TripletRel1:StreamRel1	-0.21798	0.12933	-1.686	0.09189	
TripletMemberc:AgeGroup1:TripletRel1	-0.54571	0.19058	-2.863	0.00419	*
TripletMemberc:AgeGroup1:StreamRel1	0.02263	0.19018	0.119	0.90529	
TripletMemberc:TripletRel1:StreamRel1	0.26686	0.19226	1.388	0.16513	
AgeGroup1:TripletRel1:StreamRel1	-0.19127	0.25582	-0.748	0.45465	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-0.09772	0.3803	-0.257	0.79721	

Accuracy Model: Experiment IIa, Unattended Stream Formula: Response ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Participant	(Intercept)	0.20617	0.4541		
	TripletMemberc	0.12216	0.3495	0.37	
	TripletRel1	0.12002	0.3464	0.24	0.06
Item	(Intercept)	0.05004	0.2237		
Number of obs: 11232, groups: Participant, 59; Item, 55					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.13849	0.07655	14.873	< 2e-16	*
TripletMemberc	0.26894	0.07348	3.66	0.000252	*
AgeGroup1	-0.23402	0.13471	-1.737	0.082351	
TripletRel1	0.5089	0.08997	5.656	1.55E-08	*
StreamRel1	-0.05855	0.06359	-0.921	0.357164	
TripletMemberc:AgeGroup1	-0.16082	0.13204	-1.218	0.223236	
TripletMemberc:TripletRel1	-0.47282	0.11871	-3.983	6.80E-05	*
AgeGroup1:TripletRel1	-0.41946	0.1565	-2.68	0.007356	*
TripletMemberc:StreamRel1	-0.27207	0.0933	-2.916	0.003545	*
AgeGroup1:StreamRel1	0.09458	0.12646	0.748	0.454507	
TripletRel1:StreamRel1	0.16016	0.1272	1.259	0.207983	
TripletMemberc:AgeGroup1:TripletRel1	0.58921	0.18606	3.167	0.001541	*
TripletMemberc:AgeGroup1:StreamRel1	0.18377	0.18538	0.991	0.321548	
TripletMemberc:TripletRel1:StreamRel1	0.50918	0.18661	2.729	0.006361	*
AgeGroup1:TripletRel1:StreamRel1	0.15879	0.25283	0.628	0.529986	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-0.48535	0.3705	-1.31	0.190205	

Accuracy Model: Experiment IIa, Both Streams					
Formula: Response ~ TripletMember * AgeGroup * Stream * TripletRel * StreamRel+(1+TripletMember+Stream|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Item	(Intercept)	0.0708	0.2661		
Participant	(Intercept)	0.21694	0.4658		
	Triplet Memberc	0.1041	0.3226	0.23	
	Stream1	0.01026	0.1013	0.21	0.27
Number of obs: 22464, groups: Item, 69; Participant, 59					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.160925	0.07366	15.761	< 2e-16	*
TripletMemberc	0.335556	0.059146	5.673	1.40E-08	*
AgeGroup1	-0.171532	0.129751	-1.322	0.186165	
Stream1	-0.047035	0.053876	-0.873	0.382651	
TripletRel1	0.179486	0.048989	3.664	0.000248	*
StreamRel1	-0.003854	0.044979	-0.086	0.931724	
TripletMemberc:AgeGroup1	-0.211356	0.108527	-1.947	0.051476	
TripletMemberc:Stream1	-0.145167	0.073692	-1.97	0.048847	.
AgeGroup1:Stream1	-0.156024	0.09387	-1.662	0.09649	
TripletMemberc:TripletRel1	0.084405	0.075949	1.111	0.266423	
AgeGroup1:TripletRel1	-0.180907	0.08966	-2.018	0.043623	.
Stream1:TripletRel1	0.506686	0.105445	4.805	1.55E-06	*
TripletMemberc:StreamRel1	-0.186061	0.066593	-2.794	0.005206	*
AgeGroup1:StreamRel1	0.066813	0.089655	0.745	0.456136	
Stream1:StreamRel1	-0.111766	0.090132	-1.24	0.214969	
TripletRel1:StreamRel1	-0.029538	0.089989	-0.328	0.742731	
TripletMemberc:AgeGroup1:Stream1	0.12882	0.132542	0.972	0.331093	
TripletMemberc:AgeGroup1:TripletRel1	0.007655	0.132561	0.058	0.953949	
TripletMemberc:Stream1:TripletRel1	-1.008349	0.158739	-6.352	2.12E-10	*
AgeGroup1:Stream1:TripletRel1	-0.466521	0.179155	-2.604	0.009214	.
TripletMemberc:AgeGroup1:StreamRel1	0.101516	0.132554	0.766	0.443768	
TripletMemberc:Stream1:StreamRel1	-0.176187	0.133244	-1.322	0.18607	
AgeGroup1:Stream1:StreamRel1	0.058628	0.179112	0.327	0.743422	
TripletMemberc:TripletRel1:StreamRel1	0.370957	0.133214	2.785	0.005358	*
AgeGroup1:TripletRel1:StreamRel1	-0.014193	0.179291	-0.079	0.936905	
Stream1:TripletRel1:StreamRel1	0.375887	0.180271	2.085	0.037058	.
TripletMemberc:AgeGroup1:Stream1:TripletRel1	1.146258	0.264861	4.328	1.51E-05	*
TripletMemberc:AgeGroup1:Stream1:StreamRel1	0.155813	0.26482	0.588	0.556283	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-0.27466	0.265086	-1.036	0.300147	
TripletMemberc:Stream1:TripletRel1:StreamRel1	0.250214	0.26649	0.939	0.34777	
AgeGroup1:Stream1:TripletRel1:StreamRel1	0.334454	0.358223	0.934	0.350485	
TripletMemberc:AgeGroup1:Stream1: TripletRel1:StreamRel1	-0.391891	0.529708	-0.74	0.459407	

Table 8: Reaction time models for Experiment IIb

RT Model: Experiment IIb, Attended Stream Formula: RT ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Item	(Intercept)	2438	49.37			
Participant	(Intercept)	4201	64.81			
	TripletMemberc	1322	36.36	0.04		
	TripletRel1	1038	32.21	0.03	0.49	
Residual		45522	213.36			
Number of obs: 6601, groups: Item, 60; Participant, 52						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	658.1677	11.9493	90.2559	55.08	< 2e-16	*
TripletMemberc	-66.2772	8.9091	105.7659	-7.439	2.80E-11	*
AgeGroup1	32.6669	16.2559	105.5316	2.01	0.04703	.
TripletRel1	-1.4071	10.7949	236.013	-0.13	0.8964	
StreamRel1	0.1112	7.4995	6460.229	0.015	0.98817	
TripletMemberc:AgeGroup1	-27.5737	14.1624	62.1018	-1.947	0.05607	
TripletMemberc:TripletRel1	-115.551	14.2702	1462.598	-8.097	1.17E-15	*
AgeGroup1:TripletRel1	24.9077	17.2386	136.6948	1.445	0.15078	
TripletMemberc:StreamRel1	-13.2602	10.5977	6461.955	-1.251	0.2109	
AgeGroup1:StreamRel1	-9.7497	14.99	6459.661	-0.65	0.51545	
TripletRel1:StreamRel1	2.6735	14.9821	6457.052	0.178	0.85838	
TripletMemberc:AgeGroup1:TripletRel1	-56.7946	21.1519	6444.237	-2.685	0.00727	*
TripletMemberc:AgeGroup1:StreamRel1	8.1847	21.1756	6456.586	0.387	0.69913	
TripletMemberc:TripletRel1:StreamRel1	3.8769	21.1671	6458.814	0.183	0.85468	
AgeGroup1:TripletRel1:StreamRel1	5.1251	29.9718	6456.989	0.171	0.86423	

TripletMemberc:AgeGroup1: TripletRel1:StreamRel1	-30.1409	42.3278	6456.44	-0.712	0.47644	

RT Model: Experiment IIb, Unattended Stream Formula: RT ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Item	(Intercept)	739.2	27.19			
Participant	(Intercept)	3913.9	62.56			
	TripletMemberc	1044.9	32.33	0.17		
	TripletRel1	2594.9	50.94	0.07	-0.32	
Residual		35650.4	188.81			
Number of obs: 6800, groups: Item, 55; Participant, 52						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	645.451	10.169	66.58	63.471	< 2e-16	*
TripletMemberc	-45.919	7.269	74.406	-6.317	1.76E-08	*
AgeGroup1	23.737	14.678	122.308	1.617	0.1084	
TripletRel1	5.889	10.803	108.733	0.545	0.5868	
StreamRel1	41.595	6.519	6630.015	6.381	1.88E-10	*
TripletMemberc:AgeGroup1	7.001	12.327	60.573	0.568	0.5722	
TripletMemberc:TripletRel1	12.965	12.175	420.475	1.065	0.2875	
AgeGroup1:TripletRel1	-5.6	18.414	103.112	-0.304	0.7617	
TripletMemberc:StreamRel1	-36.795	9.228	6630.891	-3.987	6.76E-05	*
AgeGroup1:StreamRel1	3.291	13.04	6636.369	0.252	0.8007	
TripletRel1:StreamRel1	75.9	13.041	6630.086	5.82	6.15E-09	*
TripletMemberc:AgeGroup1:TripletRel1	26.982	18.422	6615.901	1.465	0.143	
TripletMemberc:AgeGroup1:StreamRel1	7.078	18.454	6629.764	0.384	0.7013	
TripletMemberc:TripletRel1:StreamRel1	-155.155	18.485	6646.03	-8.394	< 2e-16	*
AgeGroup1:TripletRel1:StreamRel1	50.205	26.09	6637.962	1.924	0.0544	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-23.234	36.926	6636.556	-0.629	0.5292	

RT Model: Experiment IIb, Both Streams						
Formula: RT ~ TripletMember * AgeGroup * Stream * TripletRel * StreamRel+(1+TripletMember+Stream|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Item	(Intercept)	711.15	26.667			
Participant	(Intercept)	4070.12	63.798			
	Triplet Memberc	924.5	30.406	0.16		
	Stream1	23.65	4.864	-0.1	-1	
Residual		41557.96	203.858			
Number of obs: 13401, groups: Item, 69; Participant, 52						
Fixed effects:	Estimate	Std. Error	df	t value	Pr(>|t|)	
(Intercept)	652.409	9.836	63.714	66.326	< 2e-16	*
TripletMemberc	-60.202	5.997	66.969	-10.038	5.53E-15	*
AgeGroup1	22.422	12.957	179.82	1.73	0.085261	
Stream1	-14.613	5.671	1810.81	-2.577	0.010053	.
TripletRel1	6.312	5.462	7308.576	1.156	0.247851	
StreamRel1	20.653	5.005	13245.88	4.126	3.71E-05	*
TripletMemberc:AgeGroup1	-10.197	10.409	62.926	-0.98	0.331014	
TripletMemberc:Stream1	21.96	7.771	6950.406	2.826	0.004728	*
AgeGroup1:Stream1	-2.006	10.075	1992.653	-0.199	0.842209	
TripletMemberc:TripletRel1	-61.593	8.144	4247.579	-7.563	4.79E-14	*
AgeGroup1:TripletRel1	7.349	10.009	13246.14	0.734	0.46283	
Stream1:TripletRel1	16.027	11.688	3631.132	1.371	0.17038	
TripletMemberc:StreamRel1	-24.372	7.079	13256.92	-3.443	0.000578	*
AgeGroup1:StreamRel1	-2.892	10.009	13247.17	-0.289	0.772658	
Stream1:StreamRel1	40.96	10.005	13239.6	4.094	4.27E-05	*
TripletRel1:StreamRel1	39.896	10.015	13252.64	3.984	6.82E-05	*
TripletMemberc:AgeGroup1:Stream1	39.991	14.143	13235.37	2.828	0.004695	*
TripletMemberc:AgeGroup1:TripletRel1	-14.043	14.15	13252.96	-0.992	0.321001	
TripletMemberc:Stream1:TripletRel1	108.135	16.625	3384.605	6.504	8.95E-11	*
AgeGroup1:Stream1:TripletRel1	-28.345	19.99	13225.59	-1.418	0.156226	
TripletMemberc:AgeGroup1:StreamRel1	4.778	14.156	13253.69	0.337	0.735751	
TripletMemberc:Stream1:StreamRel1	-23.604	14.157	13245.7	-1.667	0.095487	
AgeGroup1:Stream1:StreamRel1	11.588	20.002	13235.32	0.579	0.562361	
TripletMemberc:TripletRel1:StreamRel1	-78.923	14.174	13267.58	-5.568	2.62E-08	*
AgeGroup1:TripletRel1:StreamRel1	30.289	20.031	13254.75	1.512	0.130528	
Stream1:TripletRel1:StreamRel1	73.022	19.995	13231.96	3.652	0.000261	*
TripletMemberc:AgeGroup1: Stream1:TripletRel1	82.547	28.272	13226.85	2.92	0.003509	*
TripletMemberc:AgeGroup1: Stream1:StreamRel1	-4.507	28.299	13237.16	-0.159	0.873468	
TripletMemberc:AgeGroup1: TripletRel1:StreamRel1	-30.182	28.333	13261.08	-1.065	0.286779	
TripletMemberc:Stream1: TripletRel1:StreamRel1	-162.763	28.288	13229.55	-5.754	8.92E-09	*
AgeGroup1:Stream1: TripletRel1:StreamRel1	39.901	39.996	13233.8	0.998	0.318482	
TripletMemberc:AgeGroup1:Stream1: TripletRel1:StreamRel1	13.55	56.557	13224.16	0.24	0.810653	

Table 9: Accuracy Models of Experiment IIb

Accuracy Model: Experiment IIb, Attended Stream Formula: Response ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)						
Random effects:						
Groups	Name	Variance	Std.Dev.	Corr		
Item	(Intercept)	0.09218	0.3036			
Participant	(Intercept)	0.14782	0.3845			
	TripletMemberc	0.02618	0.1618	0.11		
	TripletRel1	0.11542	0.3397	-0.41		0.61
Number of obs: 10122, groups: Item, 60; Participant, 52						
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)		
(Intercept)	0.67046	0.07555	8.875	< 2e-16	*	
TripletMemberc	0.01928	0.06088	0.317	0.75144		
AgeGroup1	-0.03999	0.11172	-0.358	0.72039		
TripletRel1	-0.2017	0.08904	-2.265	0.0235	.	
StreamRel1	-0.06731	0.06073	-1.108	0.26774		
TripletMemberc:AgeGroup1	-0.179	0.09627	-1.859	0.06299		
TripletMemberc:TripletRel1	0.20076	0.11027	1.821	0.06866		
AgeGroup1:TripletRel1	0.0403	0.15086	0.267	0.78936		
TripletMemberc:StreamRel1	-0.01865	0.08616	-0.216	0.82862		
AgeGroup1:StreamRel1	0.05503	0.12151	0.453	0.65065		
TripletRel1:StreamRel1	-0.16254	0.12146	-1.338	0.18081		
TripletMemberc:AgeGroup1:TripletRel1	-0.12948	0.17233	-0.751	0.45245		
TripletMemberc:AgeGroup1:StreamRel1	-0.22393	0.17241	-1.299	0.194		
TripletMemberc:TripletRel1:StreamRel1	0.03111	0.17231	0.181	0.85671		
AgeGroup1:TripletRel1:StreamRel1	0.64541	0.243	2.656	0.00791	*	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-0.70231	0.34468	-2.038	0.04159	.	

Accuracy Model: Experiment IIb, Unattended Stream Formula: Response ~ TripletMember * AgeGroup * TripletRel * StreamRel+(1+TripletMember+TripletRel|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Item	(Intercept)	0.06329	0.2516		
Participant	(Intercept)	0.14095	0.3754		
	TripletMemberc	0.0326	0.1805	0.02	
	TripletRel1	0.09613	0.3101	-0.87	0.25
Number of obs: 10105, groups: Item, 55; Participant, 52					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	0.81002	0.07245	11.18	< 2e-16	*
TripletMemberc	-0.08019	0.06008	-1.335	0.181972	
AgeGroup1	-0.10687	0.11237	-0.951	0.341547	
TripletRel1	-0.20681	0.08855	-2.336	0.019517	.
StreamRel1	-0.23693	0.06184	-3.831	0.000127	*
TripletMemberc:AgeGroup1	-0.11773	0.10001	-1.177	0.239141	
TripletMemberc:TripletRel1	0.10972	0.1161	0.945	0.34462	
AgeGroup1:TripletRel1	0.05161	0.14746	0.35	0.726343	
TripletMemberc:StreamRel1	0.17441	0.08736	1.997	0.045878	.
AgeGroup1:StreamRel1	0.18472	0.12369	1.493	0.135347	
TripletRel1:StreamRel1	-0.38519	0.1237	-3.114	0.001846	*
TripletMemberc:AgeGroup1:TripletRel1	-0.34453	0.17479	-1.971	0.048703	.
TripletMemberc:AgeGroup1:StreamRel1	-0.36195	0.17476	-2.071	0.038345	.
TripletMemberc:TripletRel1:StreamRel1	0.20587	0.17472	1.178	0.238685	
AgeGroup1:TripletRel1:StreamRel1	-0.03163	0.24736	-0.128	0.898262	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	0.23179	0.3494	0.663	0.507081	

Accuracy Model: Experiment IIb, Both Streams					
Formula: Response ~ TripletMember * AgeGroup * Stream * TripletRel * StreamRel+(1+TripletMember+Stream|Participant)+(1|Item)					
Random effects:					
Groups	Name	Variance	Std.Dev.	Corr	
Item	(Intercept)	0.04767	0.2183		
Participant	(Intercept)	0.13489	0.3673		
	Triplet Memberc	0.02483	0.1576	0.07	
	Stream1	0.02389	0.1546	-0.23	0.67
Number of obs: 20227, groups: Item, 69; Participant, 52					
Fixed effects:	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	0.739246	0.062533	11.822	< 2e-16	*
TripletMemberc	-0.04	0.042559	-0.94	0.347274	
AgeGroup1	-0.04978	0.094967	-0.524	0.600146	
Stream1	0.144807	0.053133	2.725	0.006423	*
TripletRel1	-0.22776	0.04683	-4.863	1.15E-06	*
StreamRel1	-0.1527	0.043123	-3.541	0.000399	*
TripletMemberc:AgeGroup1	-0.14879	0.0741	-2.008	0.04465	.
TripletMemberc:Stream1	-0.08503	0.067125	-1.267	0.205279	
AgeGroup1:Stream1	-0.06029	0.095669	-0.63	0.528606	
TripletMemberc:TripletRel1	0.166056	0.070013	2.372	0.017702	.
AgeGroup1:TripletRel1	0.043084	0.086234	0.5	0.617339	
Stream1:TripletRel1	0.01874	0.099949	0.187	0.851274	
TripletMemberc:StreamRel1	0.078716	0.061039	1.29	0.197188	
AgeGroup1:StreamRel1	0.123143	0.08625	1.428	0.153362	
Stream1:StreamRel1	-0.16959	0.086233	-1.967	0.049219	.
TripletRel1:StreamRel1	-0.27568	0.086277	-3.195	0.001397	*
TripletMemberc:AgeGroup1:Stream1	0.052126	0.12209	0.427	0.669416	
TripletMemberc:AgeGroup1:TripletRel1	-0.23544	0.122061	-1.929	0.053751	.
TripletMemberc:Stream1:TripletRel1	-0.08606	0.14297	-0.602	0.547211	
AgeGroup1:Stream1:TripletRel1	0.001905	0.172511	0.011	0.991189	
TripletMemberc:AgeGroup1:StreamRel1	-0.29821	0.122091	-2.442	0.014587	.
TripletMemberc:Stream1:StreamRel1	0.18911	0.122071	1.549	0.12134	
AgeGroup1:Stream1:StreamRel1	0.124453	0.172524	0.721	0.470686	
TripletMemberc:TripletRel1:StreamRel1	0.122901	0.12209	1.007	0.314105	
AgeGroup1:TripletRel1:StreamRel1	0.318653	0.172578	1.846	0.06483	
Stream1:TripletRel1:StreamRel1	-0.22501	0.1725	-1.304	0.192105	
TripletMemberc:AgeGroup1:Stream1:TripletRel1	-0.22294	0.244303	-0.913	0.361488	
TripletMemberc:AgeGroup1:Stream1:StreamRel1	-0.12353	0.244234	-0.506	0.613009	
TripletMemberc:AgeGroup1:TripletRel1:StreamRel1	-0.25928	0.244234	-1.062	0.288411	
TripletMemberc:Stream1:TripletRel1:StreamRel1	0.17404	0.244214	0.713	0.476058	
AgeGroup1:Stream1:TripletRel1:StreamRel1	-0.66009	0.345123	-1.913	0.055796	
TripletMemberc:AgeGroup1:Stream1: TripletRel1:StreamRel1	0.933885	0.488665	1.911	0.055993	

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